Strongly eddying and yet computationally efficient: Incorporating the LANS-α turbulence model for more realistic ocean climate simulation

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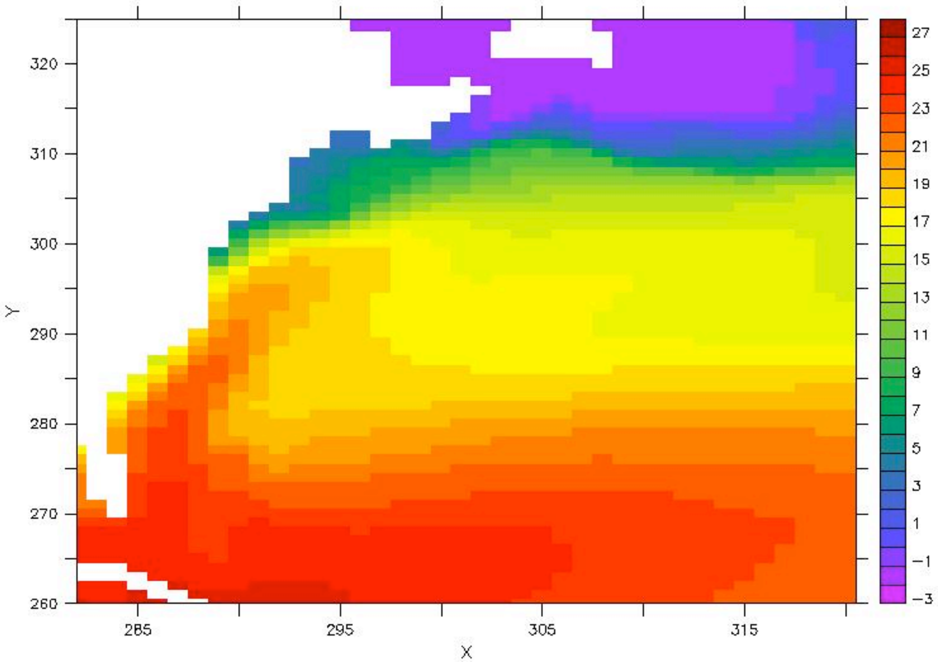
- Why consider LANS-α?
- What is LANS-α?

  and then, with choice of three turbulence parameters as the problem at hand,

- A more methodical approach to selection of parameters

a reminder: why we parameterize eddies

"IPCC-class" ocean model for Climate simulations



Surface temperature
1.0º x 1.0º grid

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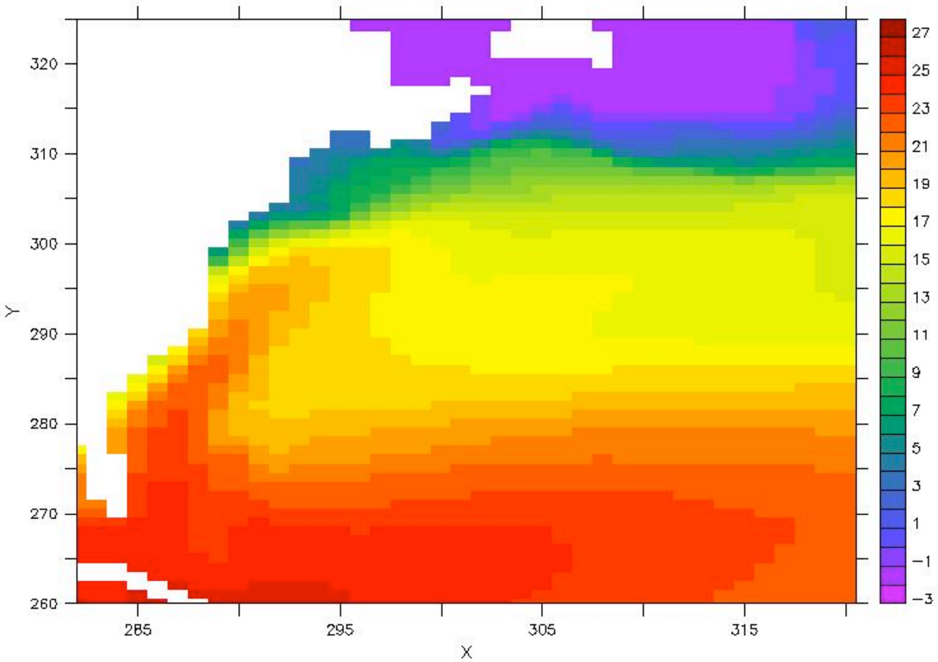

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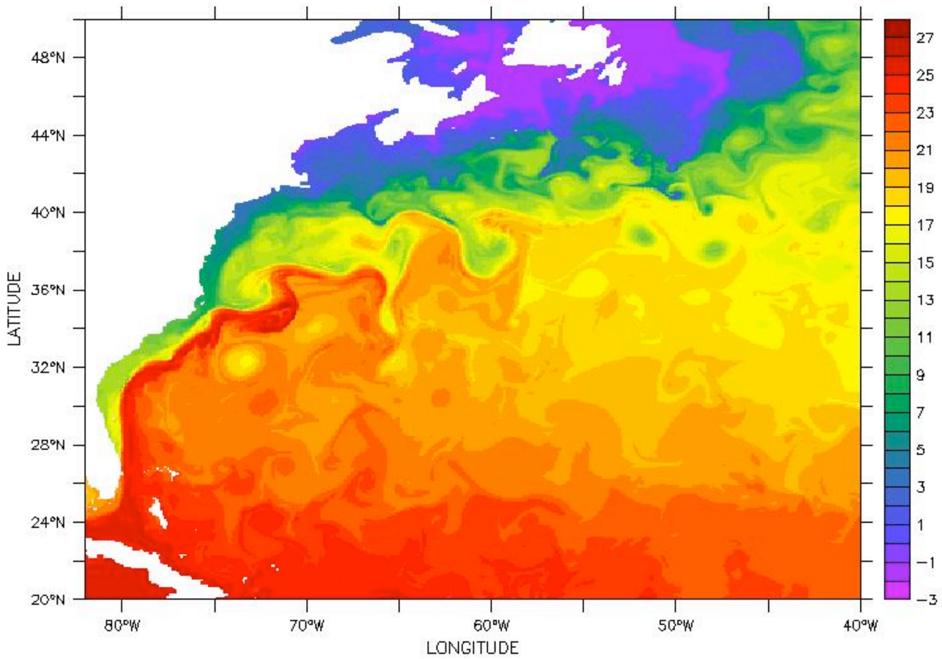
Strongly eddying simulation



Surface temperature
0.1º x 0.1º grid

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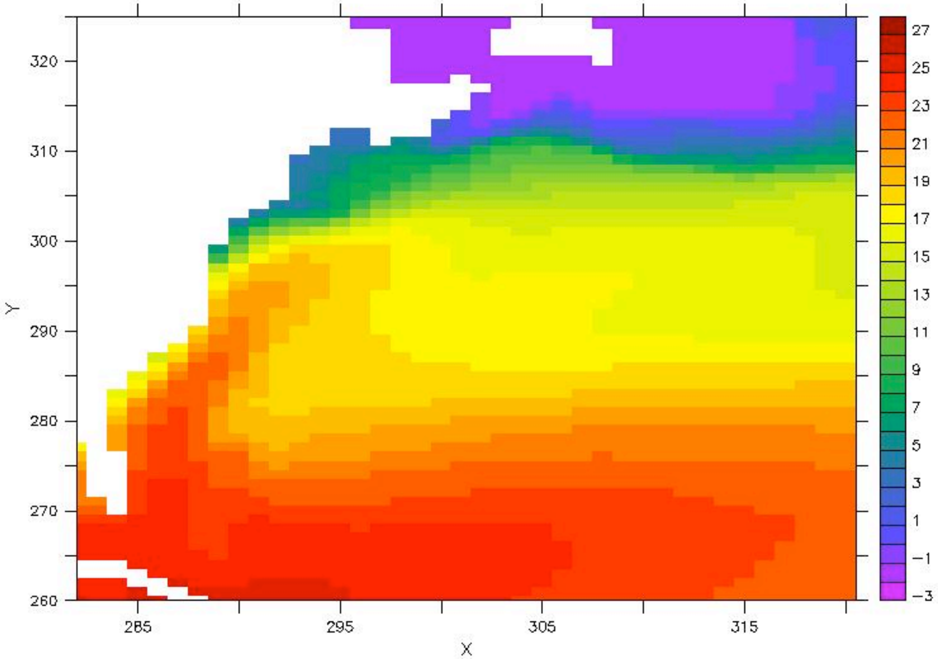

Surface temperature
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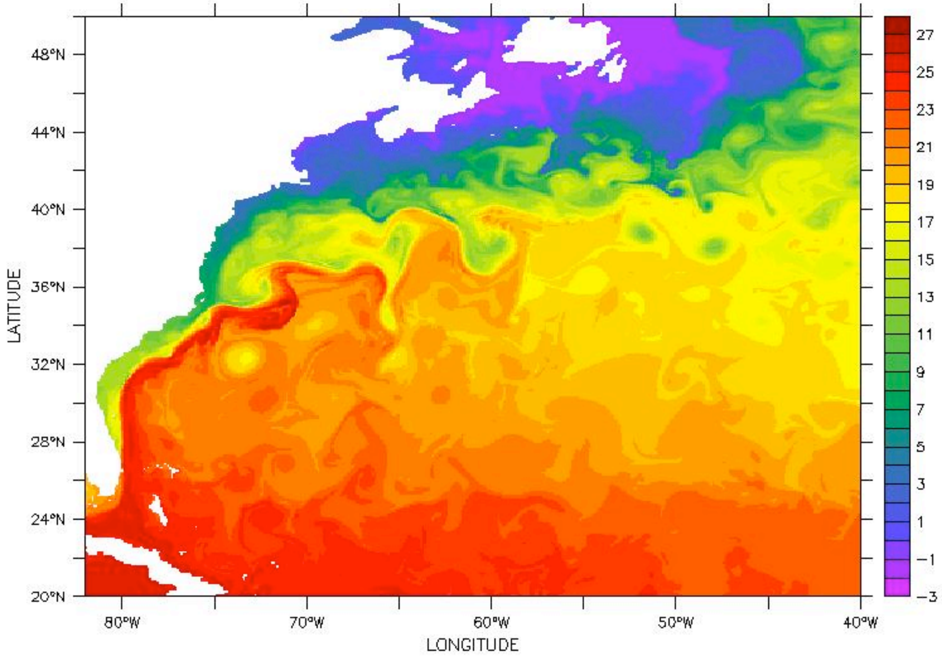

Surface temperature
0.1º x 0.1º grid

Factor of ~10 for each doubling of resolution

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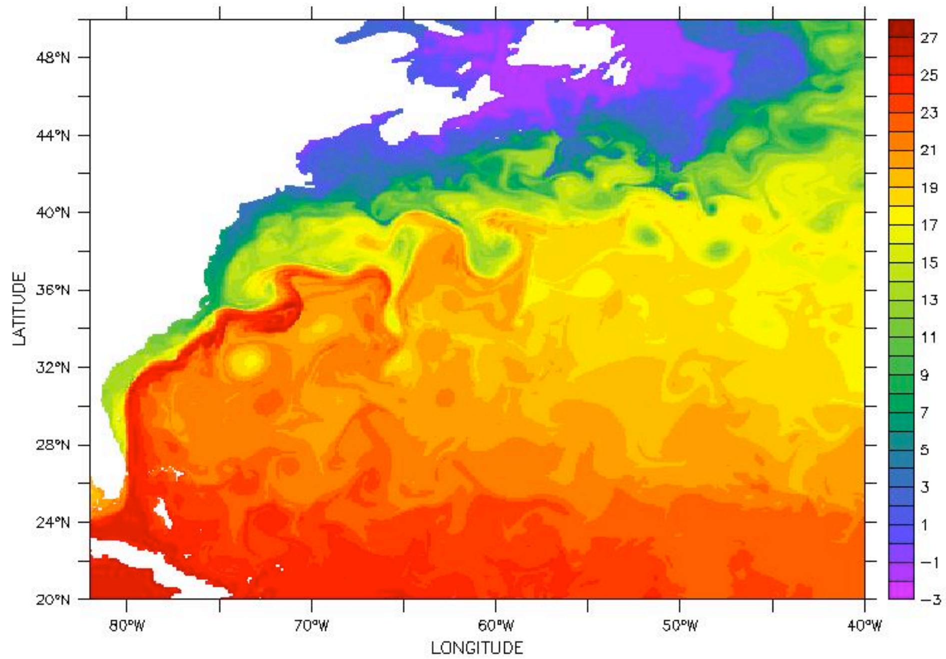
isopycnal tracer mixing schemes can parameterize much of the effect of eddies...

but some of the action of eddies has resisted parameterization (see, for example, the consideration of Southern Ocean response to changes in wind stress of Hallberg and Gnanadesikan, 2006)

Strongly eddying simulation



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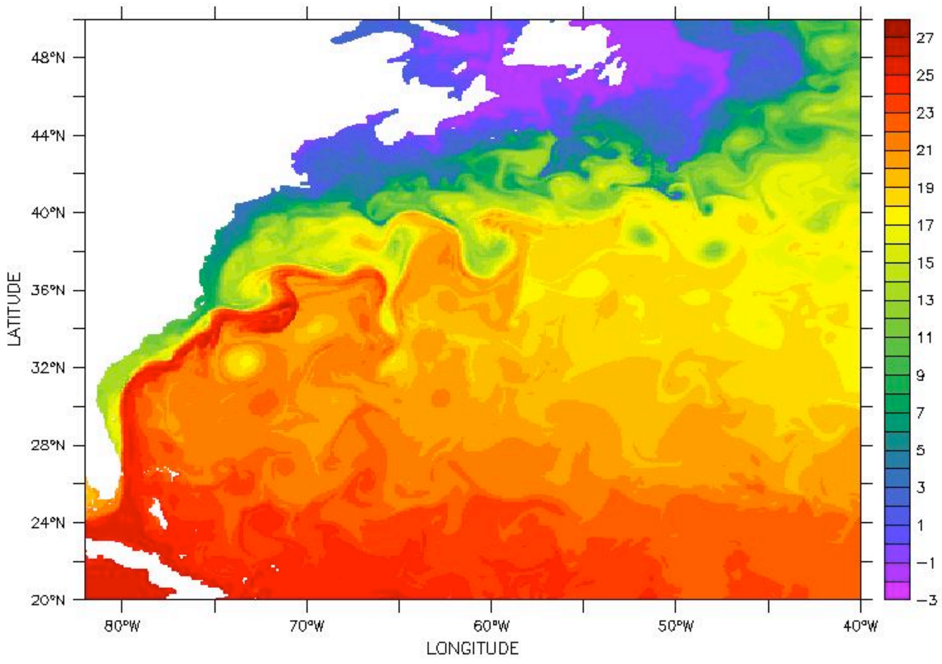
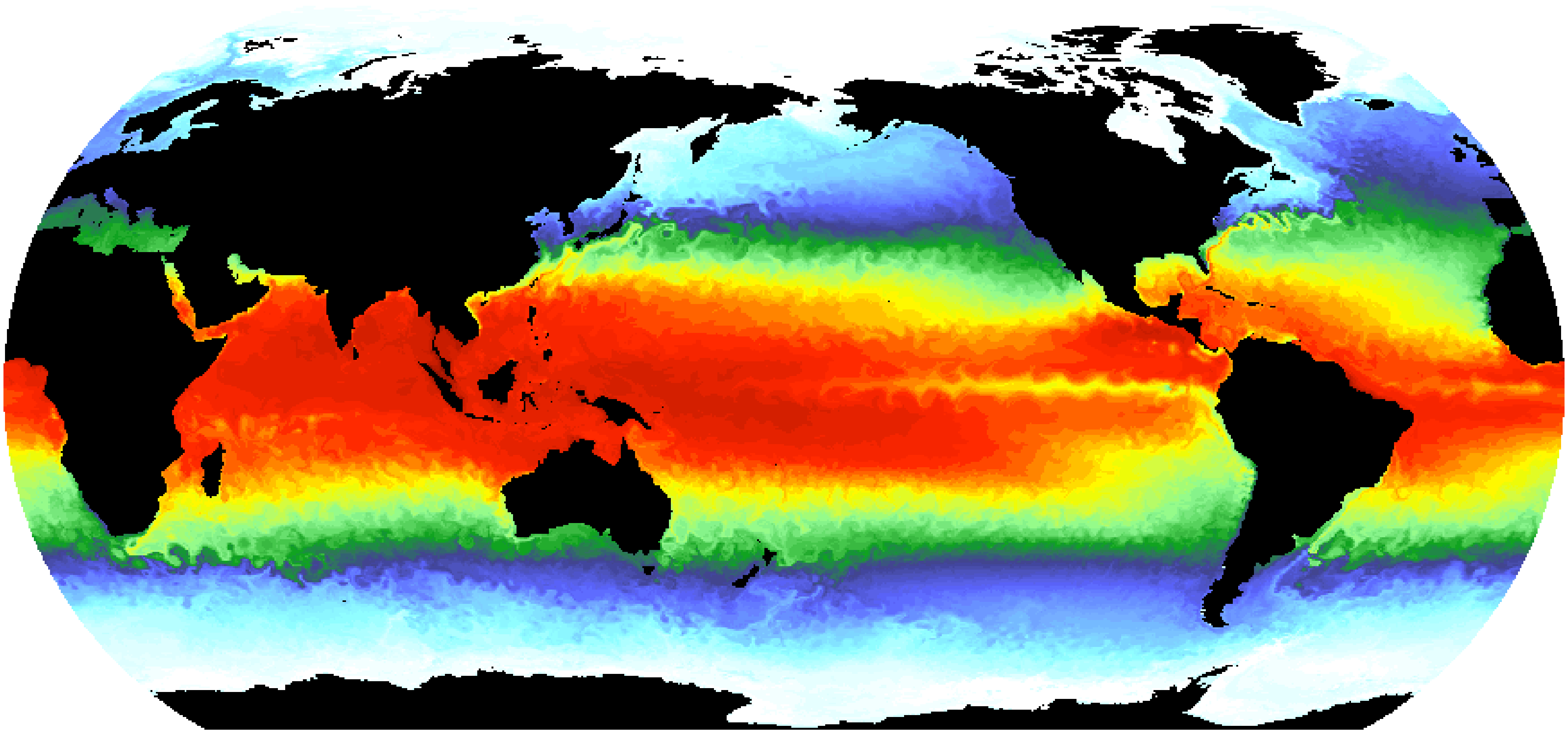
LANS-α turbulence model offers possibility of strongly eddying solution, but at ½ the resolution

Strongly eddying simulation



some of the largest computing resources are engaged in exploratory coupled climate calculations with strongly eddying models



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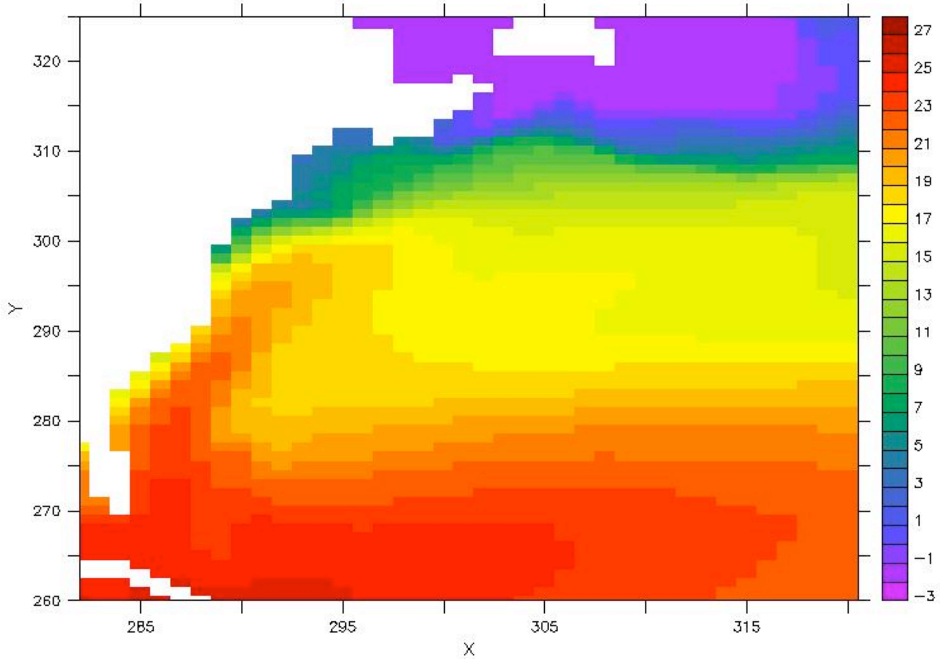
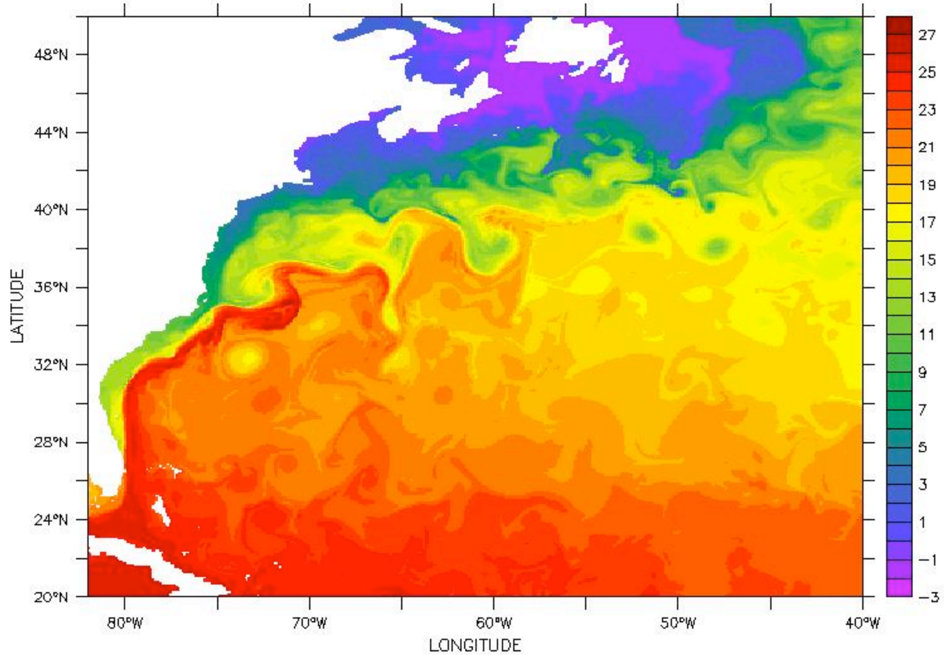


fully parameterized mesoscale,



explicitly resolved mesoscale

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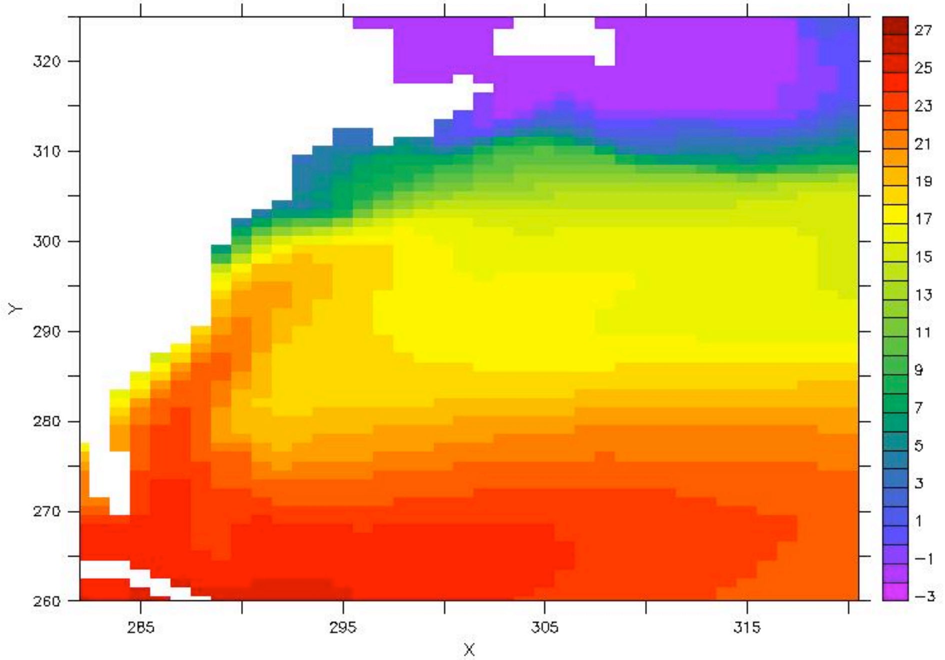

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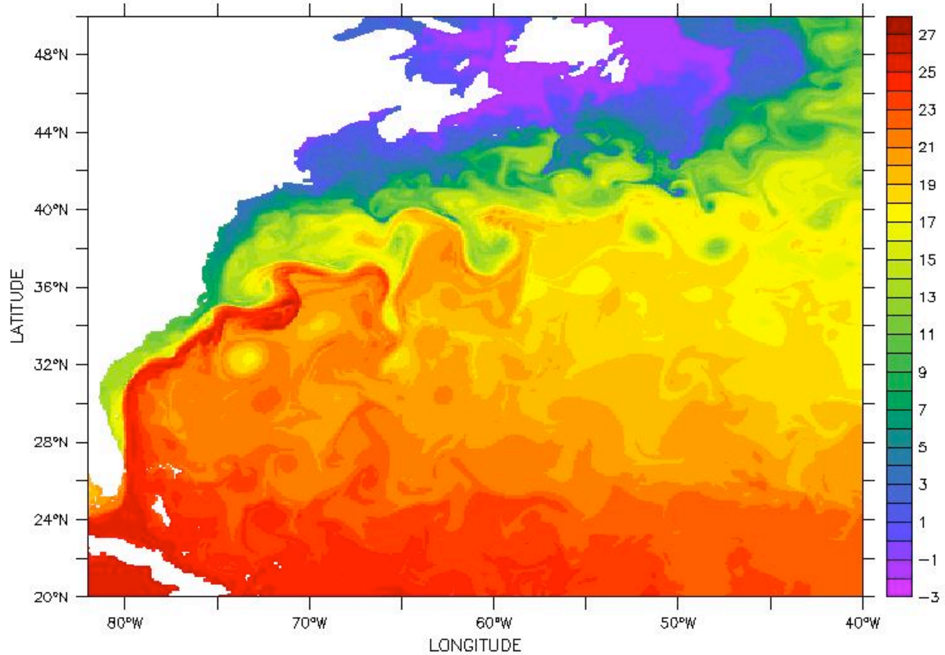

explicitly resolved mesoscale

we consider an alternative approach using LANS-α
(not the usual “eddy permitting” approach)

LANS-α to facilitate onset of mesoscale turbulence

- Lagrangian-Averaged Navier Stokes α model, based on:
  - consideration of a smoother Eulerian-averaged transporting velocity, a less smooth Lagrangian-averaged velocity transported with the flow
  - preservation of Kelvin's Circulation Theorem (LANS-α shall neither cause the flow to spin-up nor spin-down)

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Smooth Eulerian-averaged **u** and rough Lagrangian-averaged **v**

Filtering of rough velocity v produces smooth velocity u:

$$\mathbf{u} = Filter(\mathbf{v})$$

$$Filter = (1 - \alpha^2 \nabla^2)^{-1}$$

Then apply Kelvin's Circulation Theorem around a closed loop within the fluid:

$$\frac{d}{dt} \oint_{\gamma(\mathbf{u})} \mathbf{v} \cdot dx = \oint_{\gamma(\mathbf{u})} \nu \nabla^2 \mathbf{v} + \mathbf{F}$$

after manipulation, modified eqns of motion:

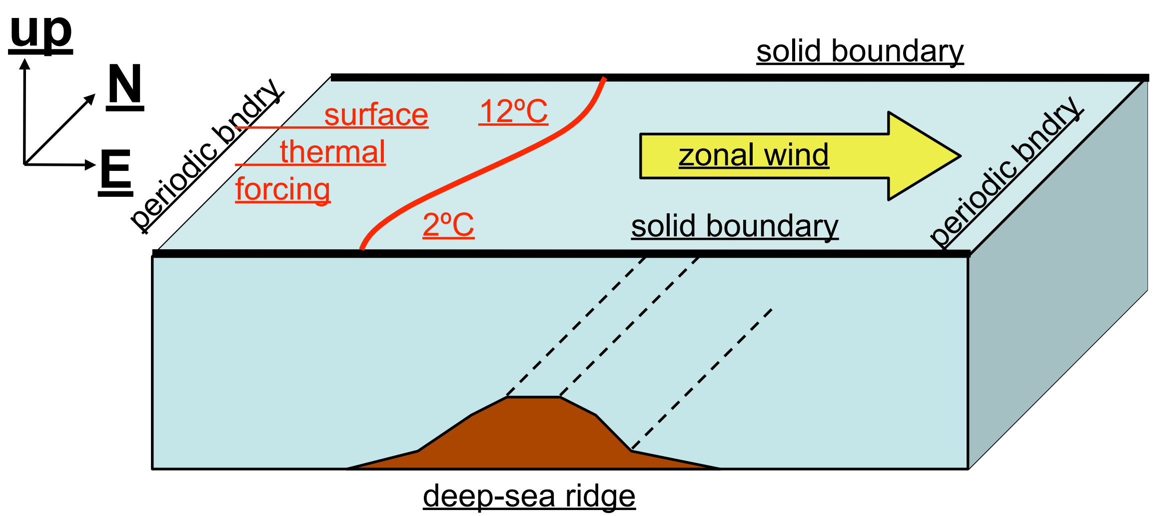
$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{v} + \nabla \mathbf{u}^{\mathrm{T}} \cdot \mathbf{v} + \nabla \pi = \nu \nabla^2 \mathbf{v} + F$$

extra nonlinear term

modified pressure

LANS-α in a Primitive Eqn Ocean Model (in POP)

test problem: a simple periodic channel flow

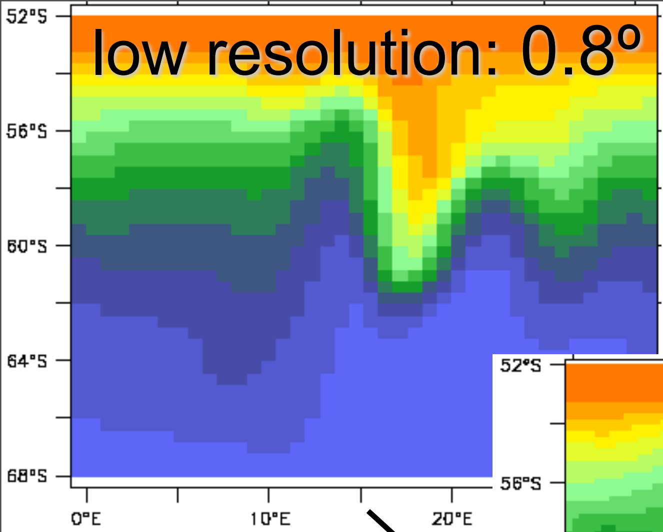


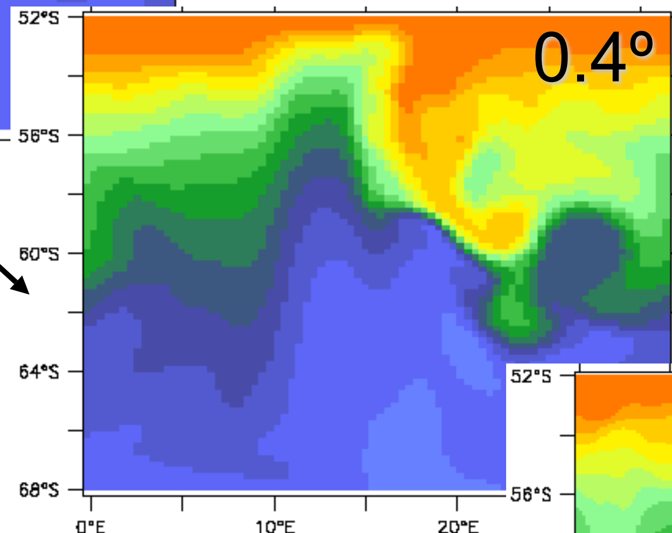
Implementation documented in Hecht, Holm, Petersen* and Wingate, JCP 2008
(along with a second paper on a highly efficient alternative implementation)
**corresponding author*

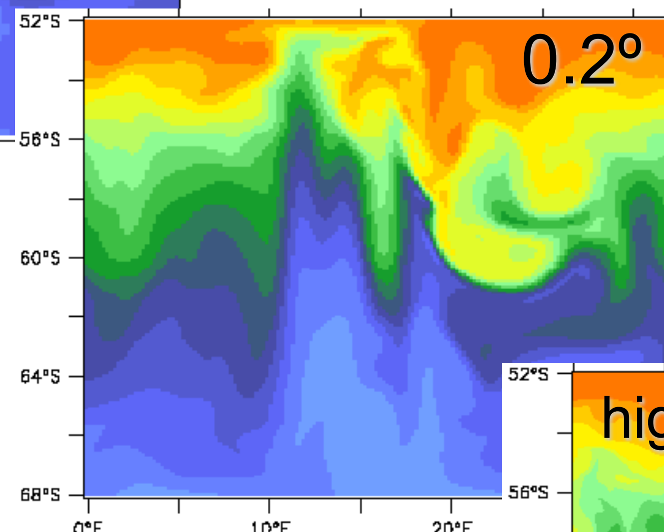
Here, we see increase in mesoscale eddy variability with resolution

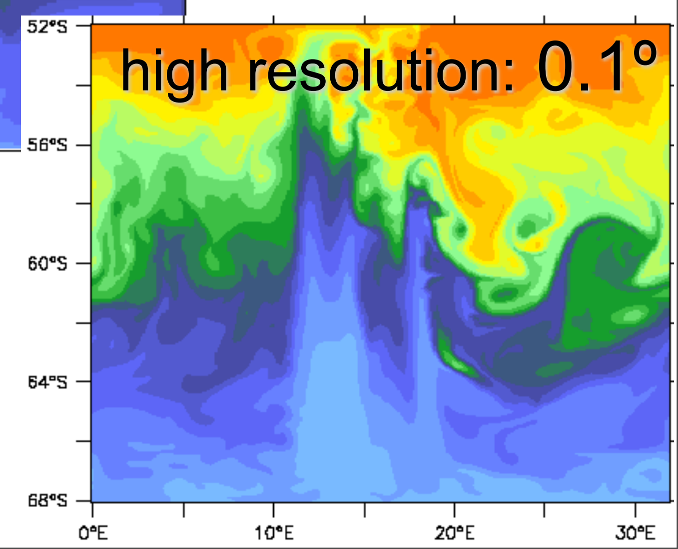
control simulations (without use of LANS-α)

cost of doubling horizontal grid is factor of 10

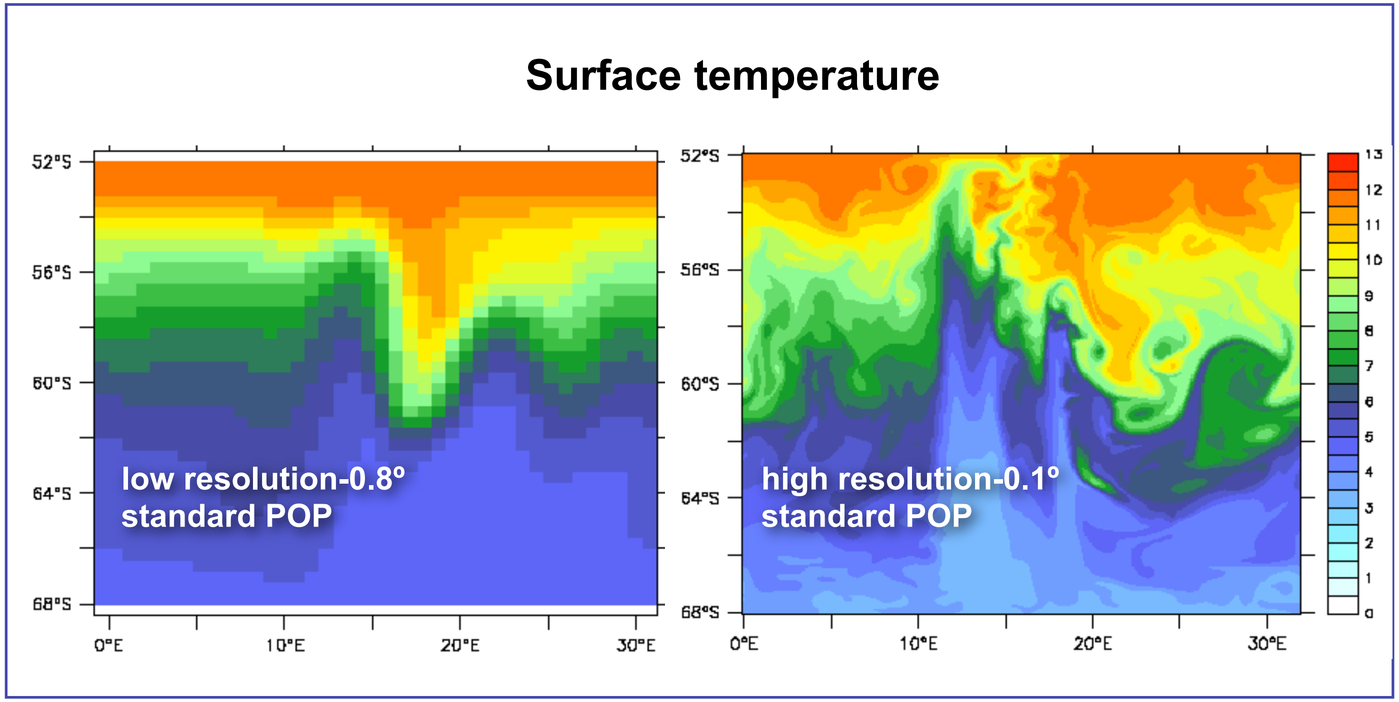


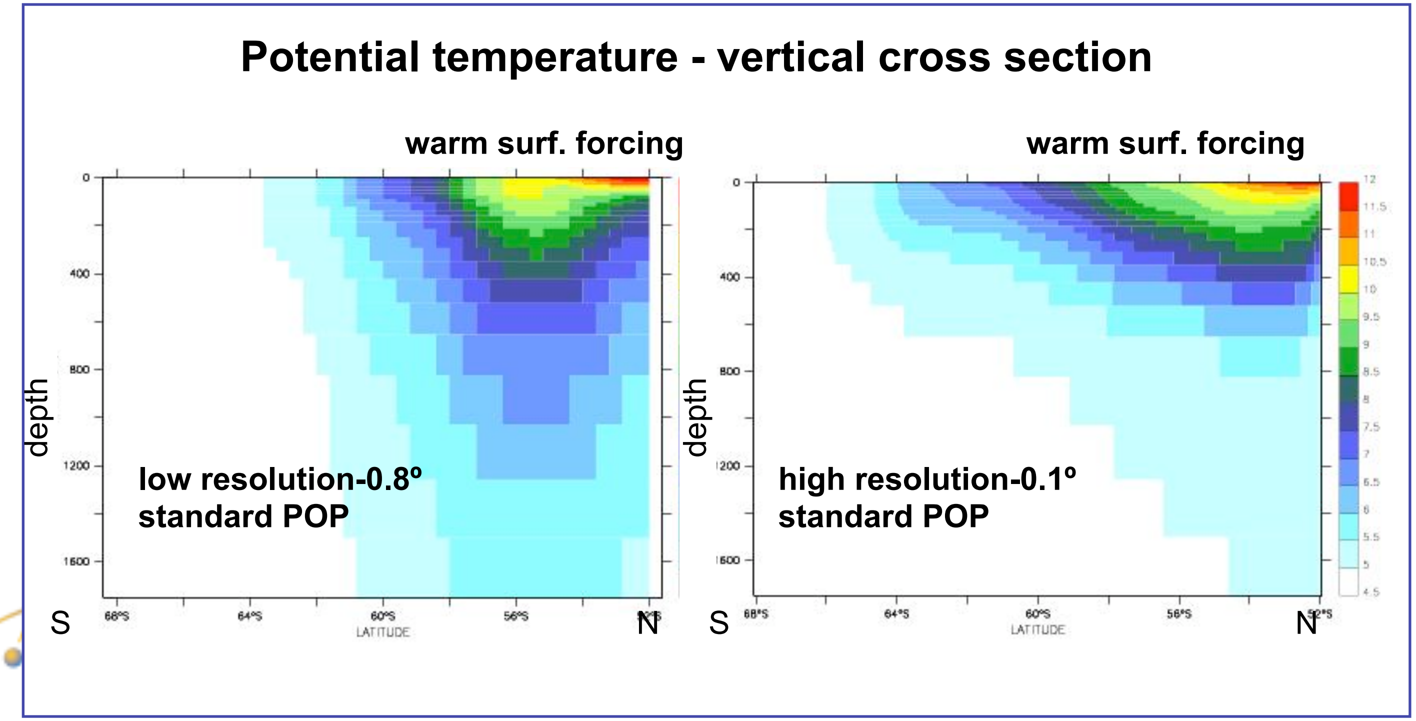






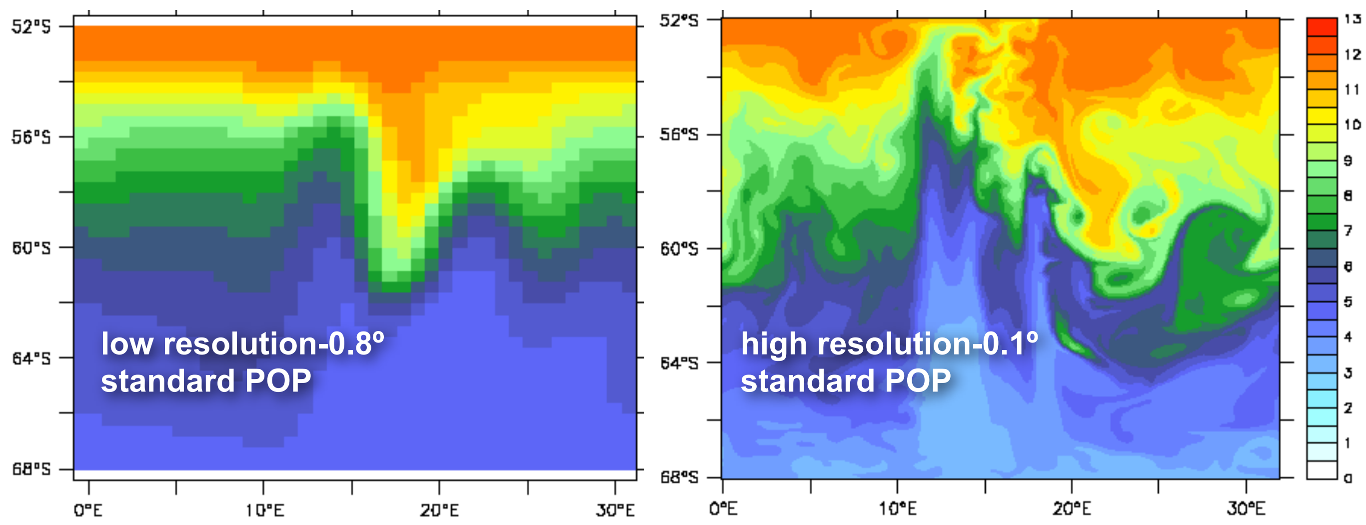
Test problem results, POP only



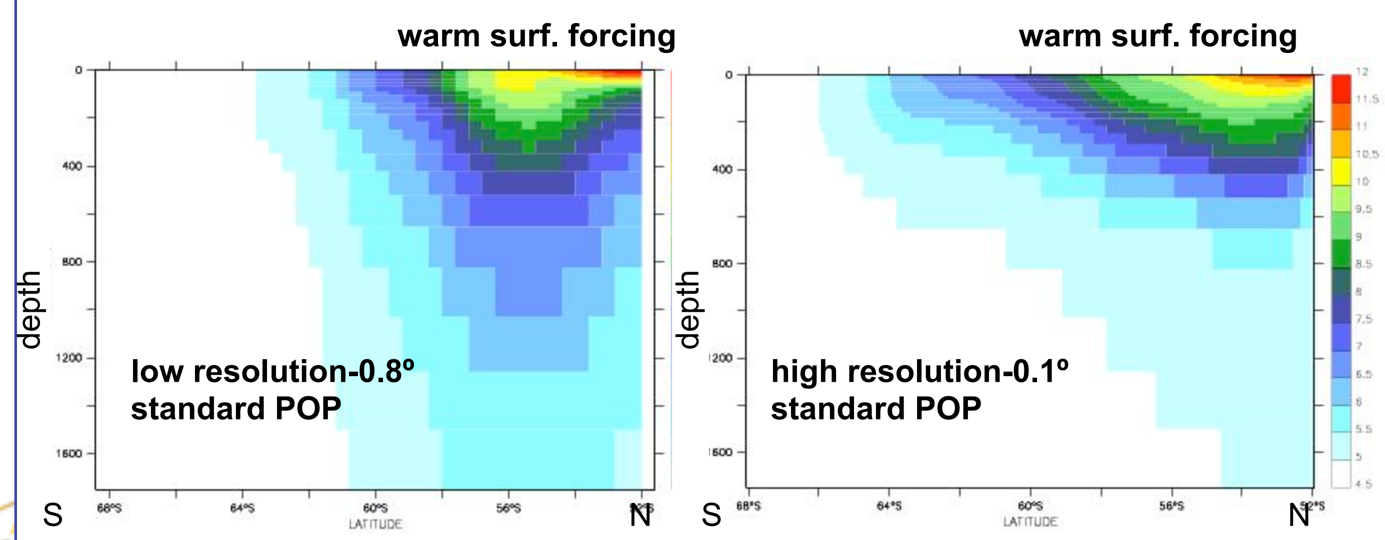


Test problem results, POP only

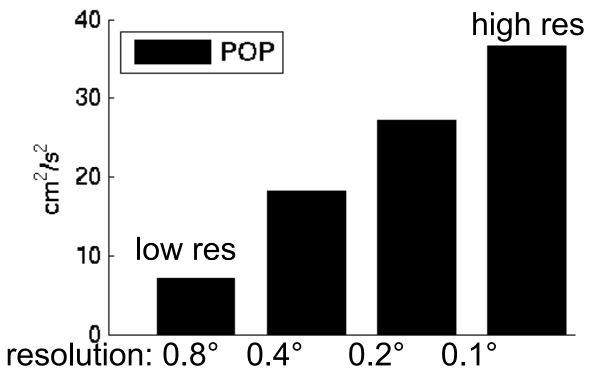
Surface temperature



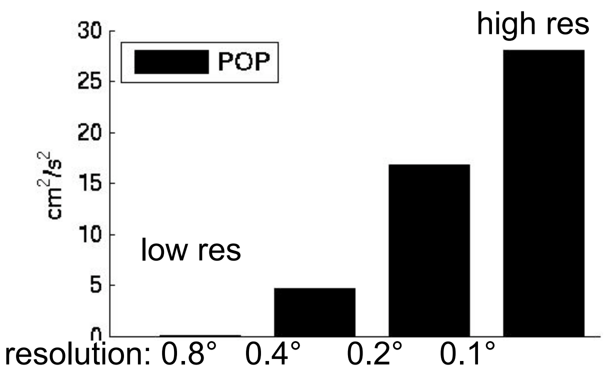
Potential temperature - vertical cross section



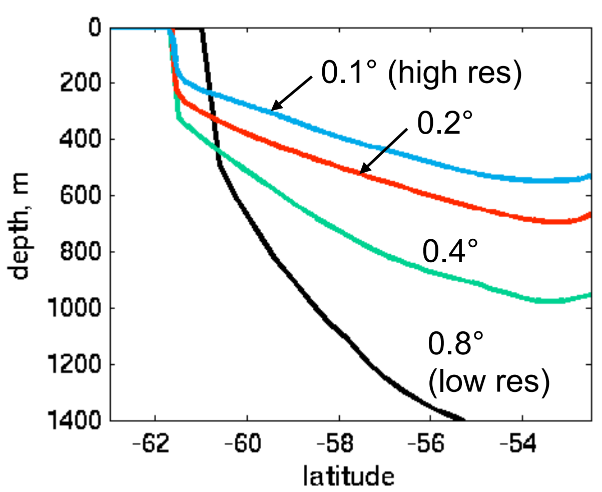
Kinetic energy



Eddy kinetic energy

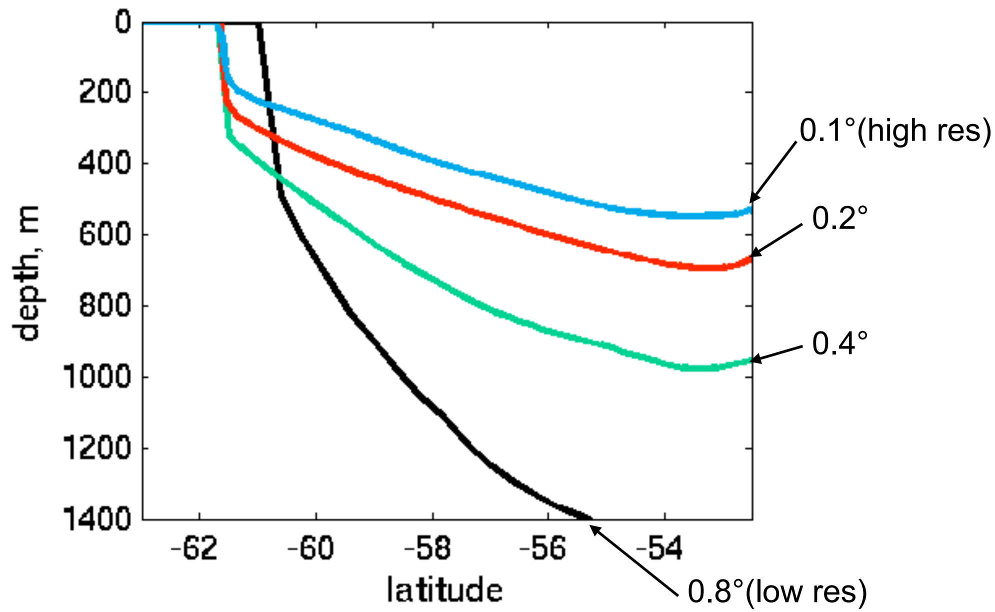


Depth of 6C isotherm

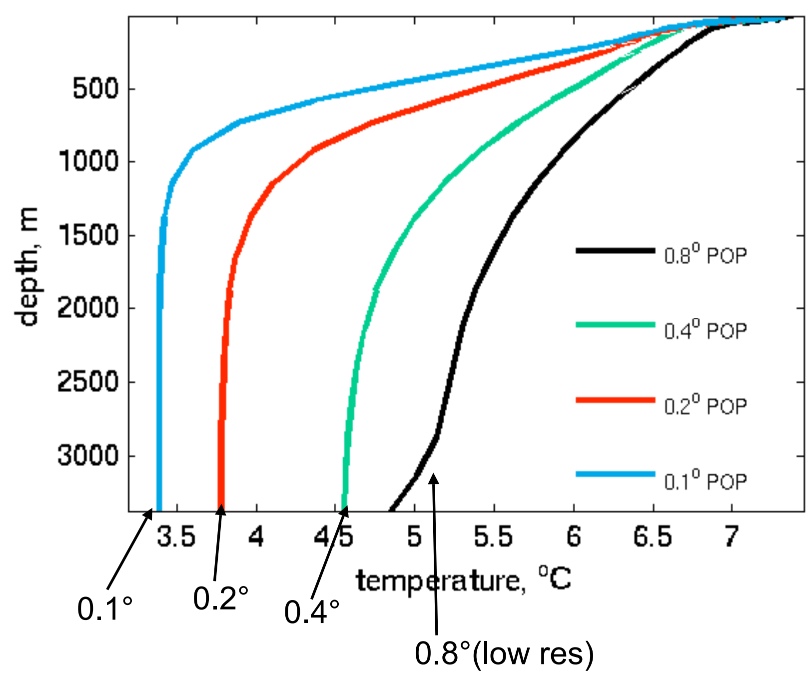


Test Problem Results, POP and POP-α

6C isotherm



Vertical temperature profile



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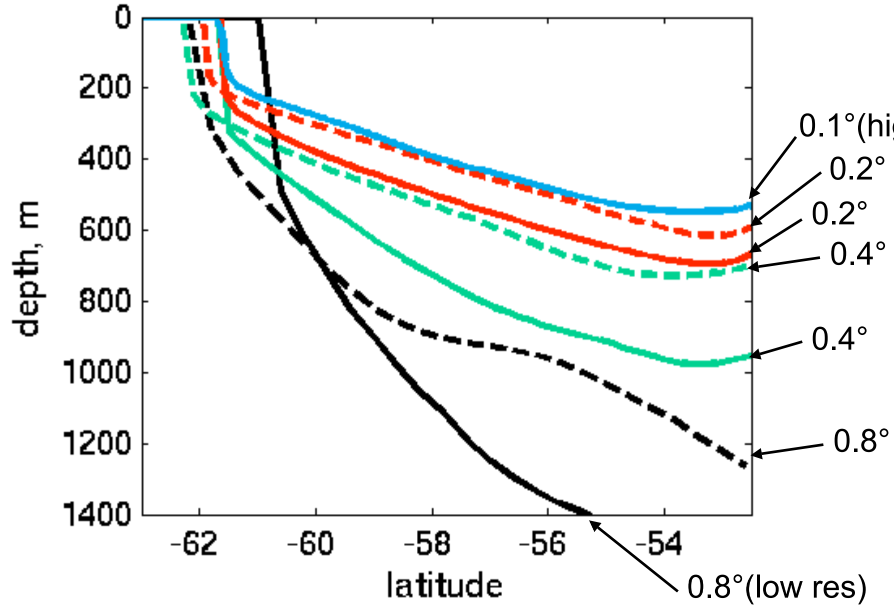

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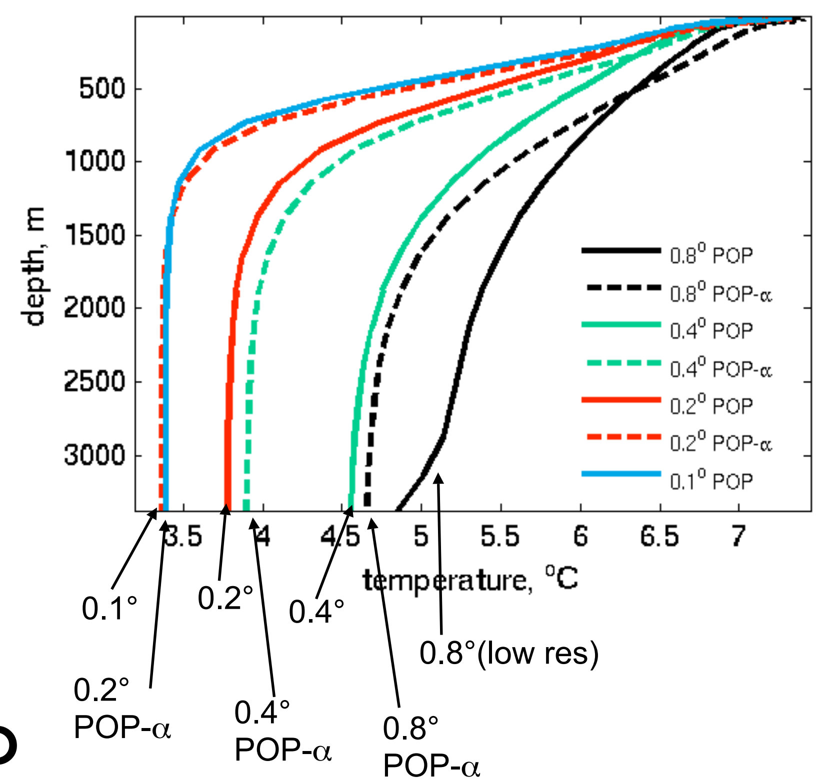
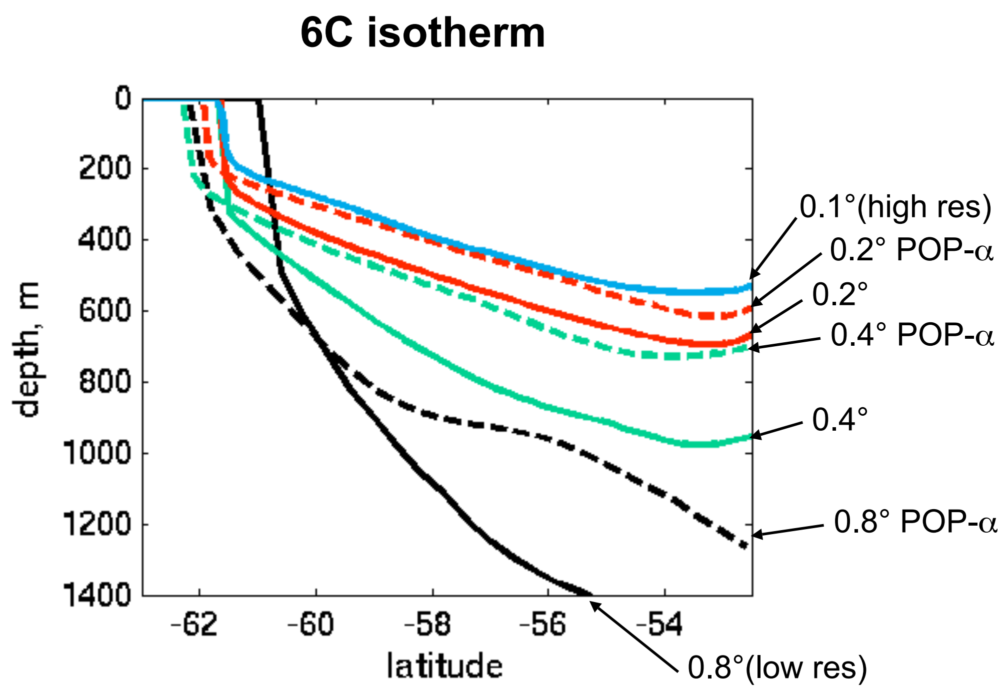
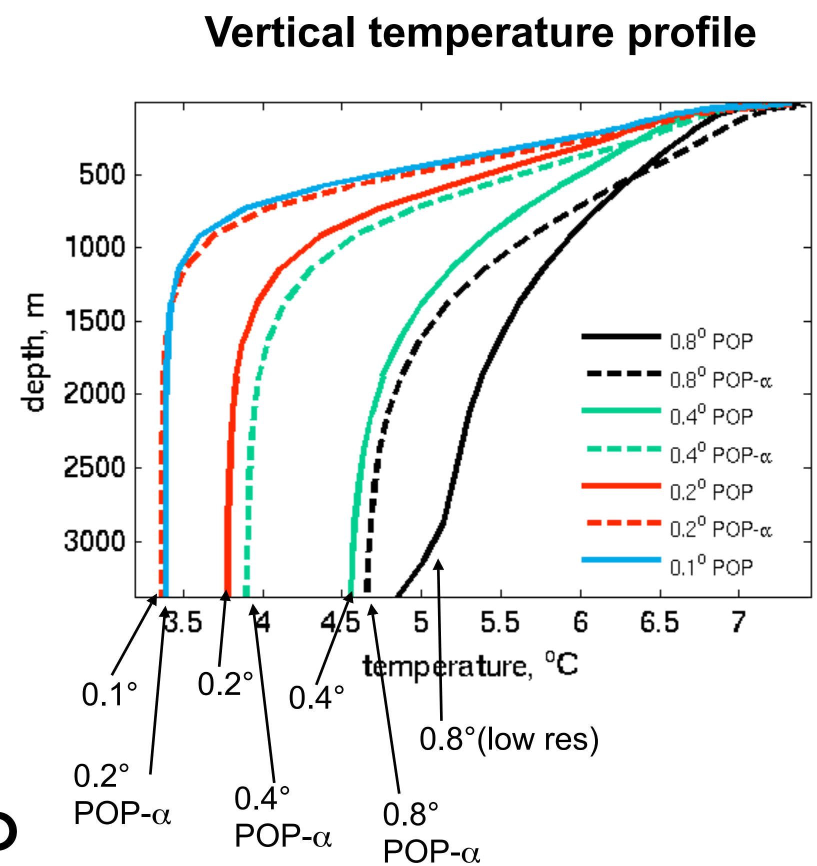


Use of LANS-α comparable to a doubling of resolution, in these measures

Test Problem Results, POP and POP-α





Use of LANS-α comparable to a doubling of resolution, in these measures

These results (from JCP 2008) produced with “standard” values of lateral viscosity, and without GM

LANS-α is an additional subgrid-scale parameterization

- How about eddy viscosity, isopycnal tracer mixing (GM)?

- if eddy viscosity is used without LANS-α then it'll be used with LANS-α
  - and probably with a larger value of eddy viscosity, as flow will be more energetic
- LANS-α not necessarily a replacement for isopycnal tracer mixing (GM)
  - even if this parameter may be made smaller
- *So, how to pick good values for each of these three coefficients?*

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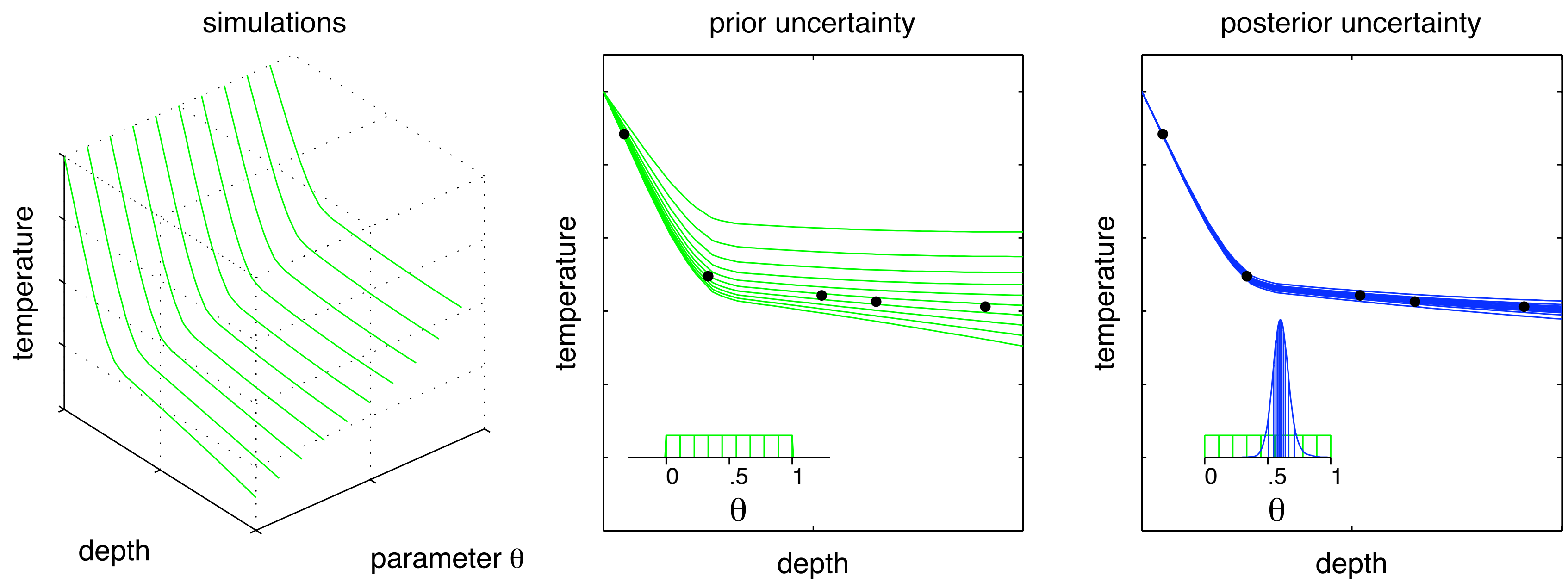
How to choose three related subgrid-scale parameters?

- Can we be methodical in choice of our three lateral turbulence parameters (α, ν, κ) as a function of resolution?
    - Can we demonstrate a better, more methodical approach to parameter estimation for climate modeling?

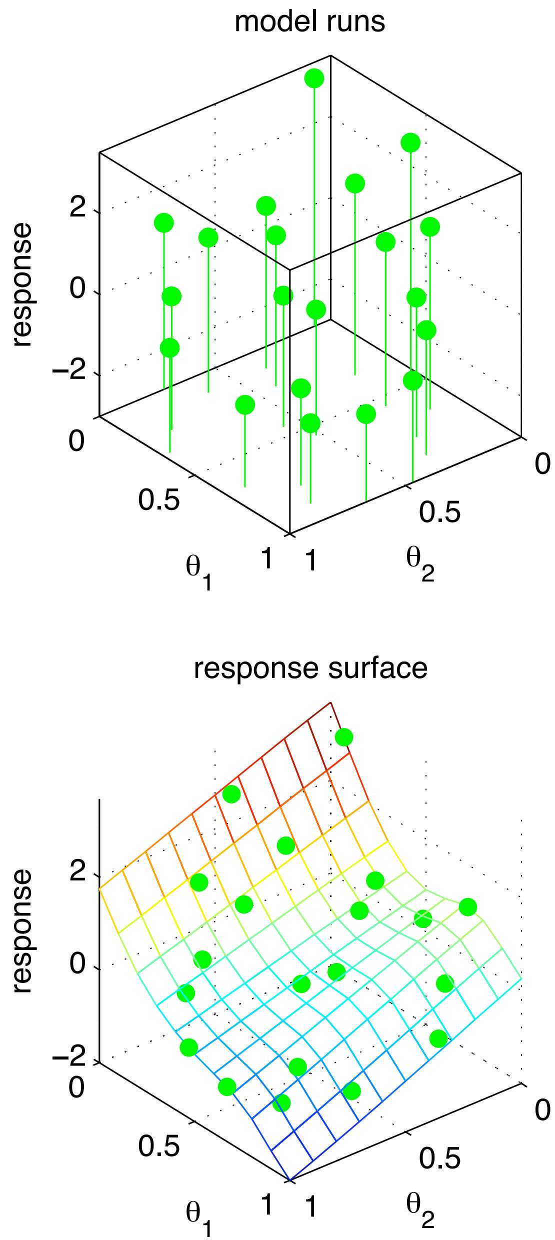
Parameter Estimation: in Concept

Use statistical approach to find input settings to match the target profile



- Finds input parameter settings that best match the target temperature profile
- Requires that initial ranges for the parameters be specified
- Here we show a 1-d parameter space – actual application uses a 3-d parameter space.

Construct a response surface of the simulation output to predict at untried settings



- Actual application requires a basis representation to predict temperature profiles
- Can use holdouts to assess accuracy of response surface
- Can carry out sensitivity analysis using response surface

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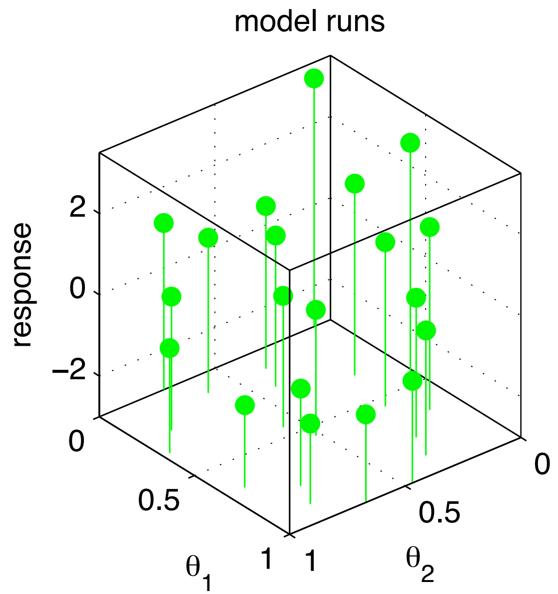

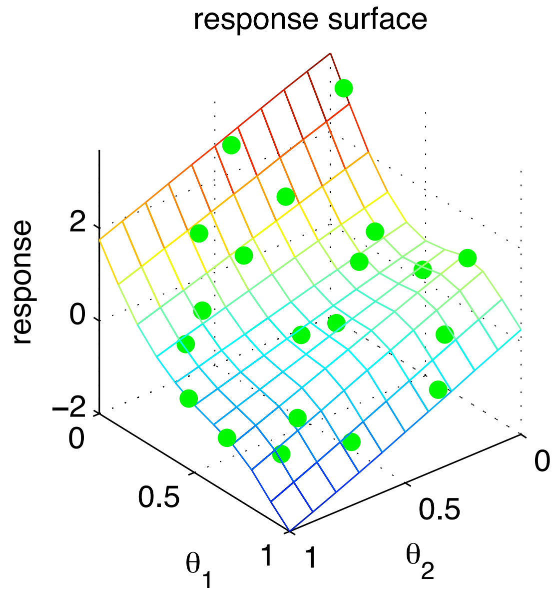

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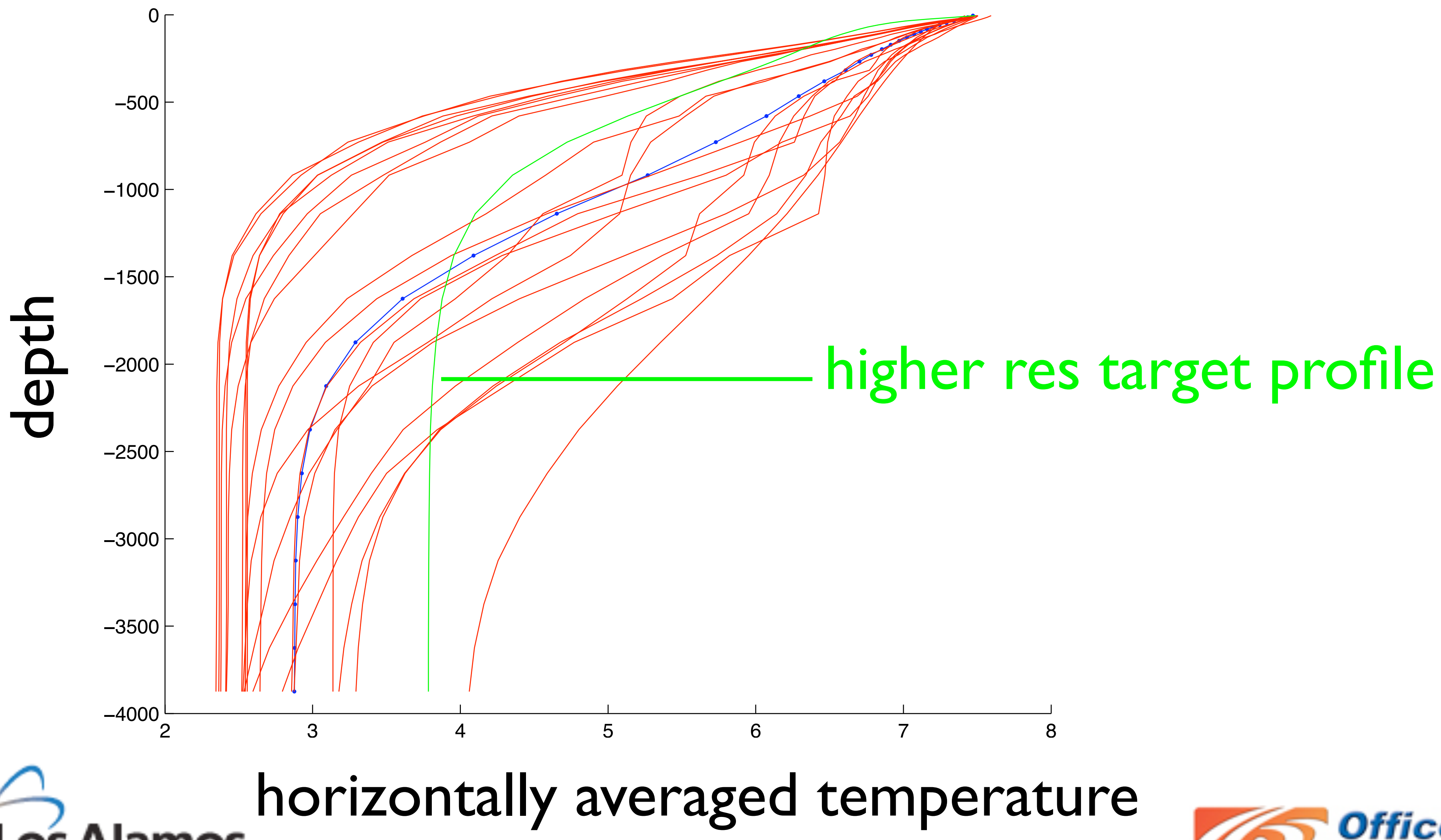
Prediction at untried settings based on Gaussian process emulators (there's a literature on this)

Parameter Estimation: in Practice



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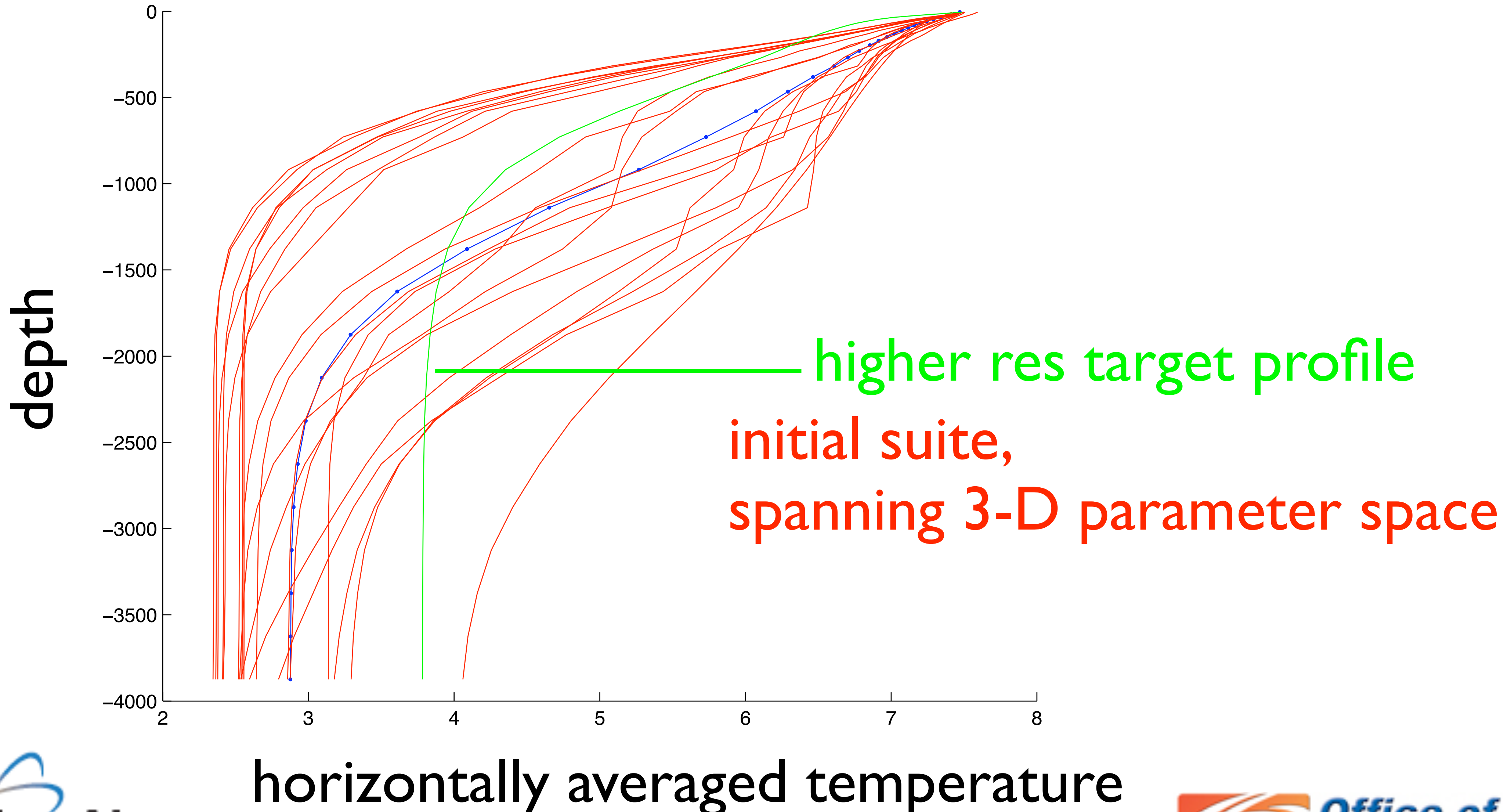

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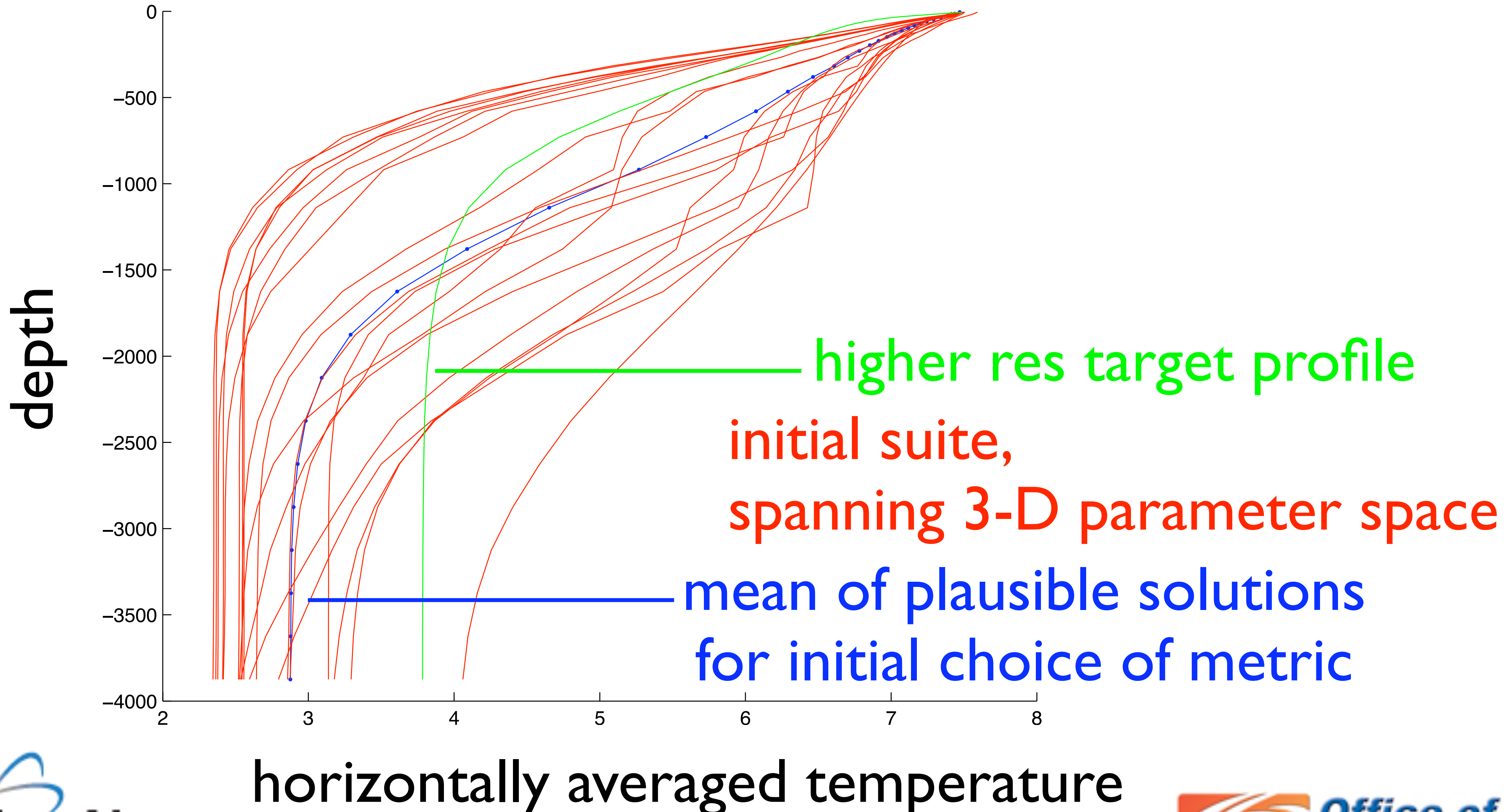
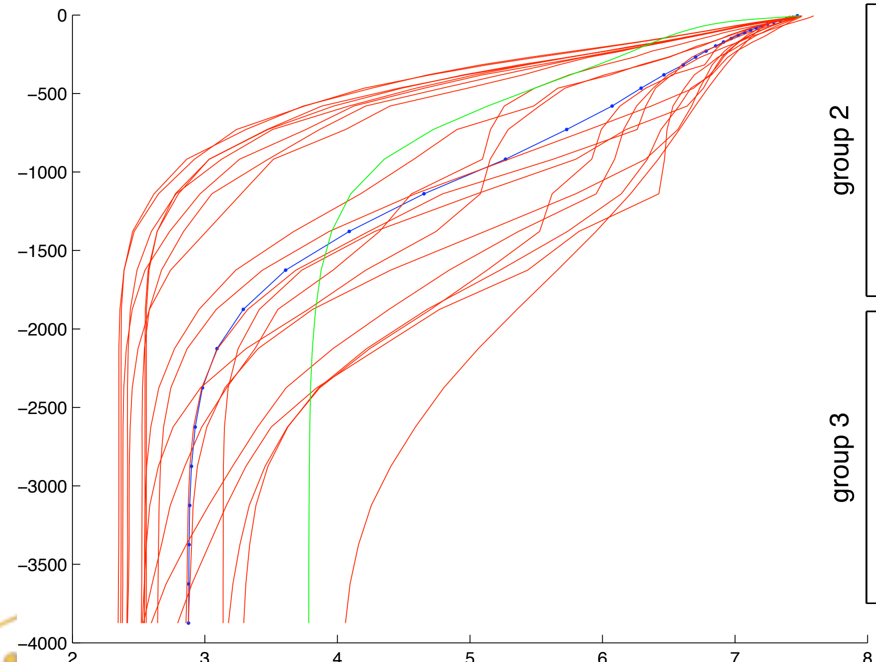
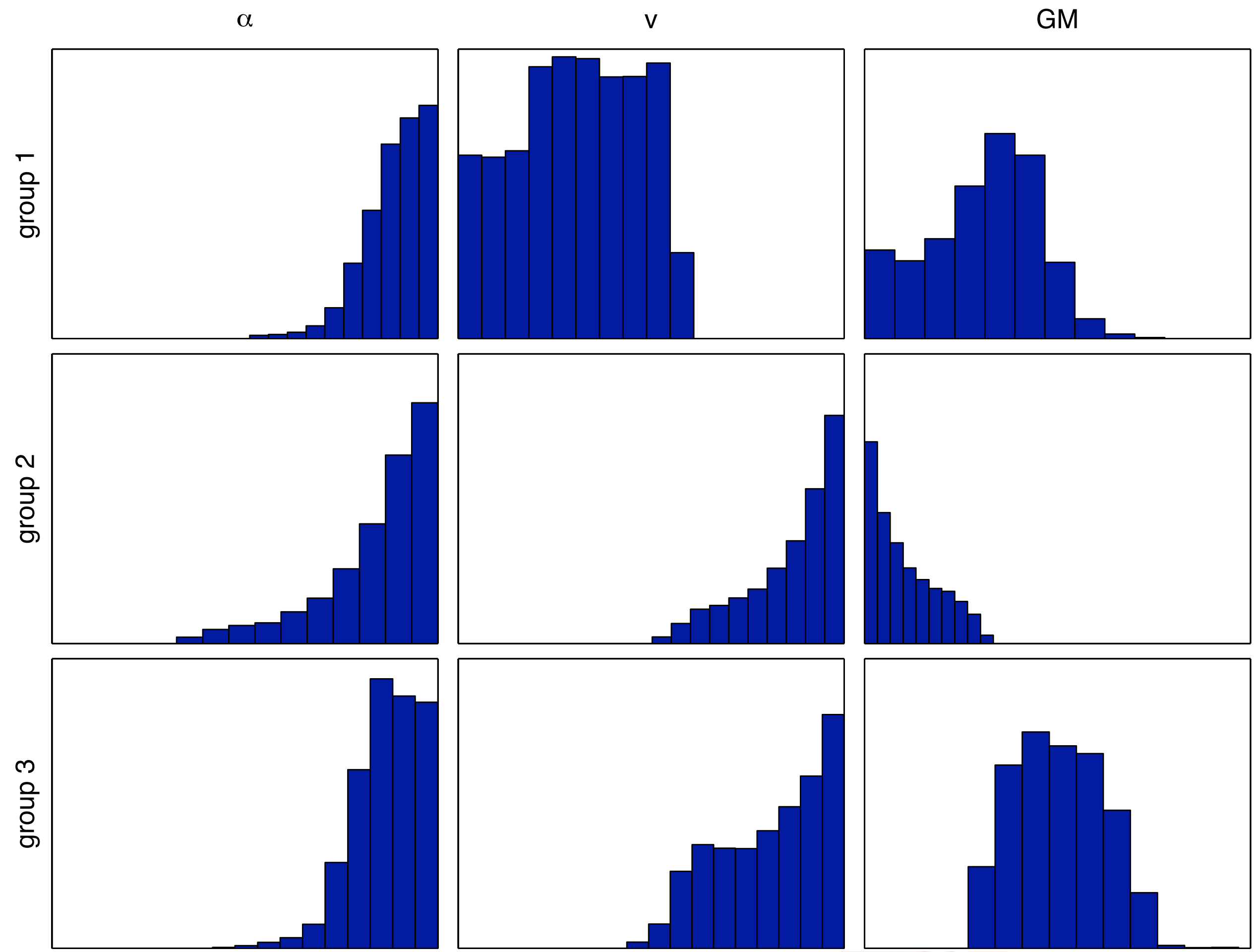


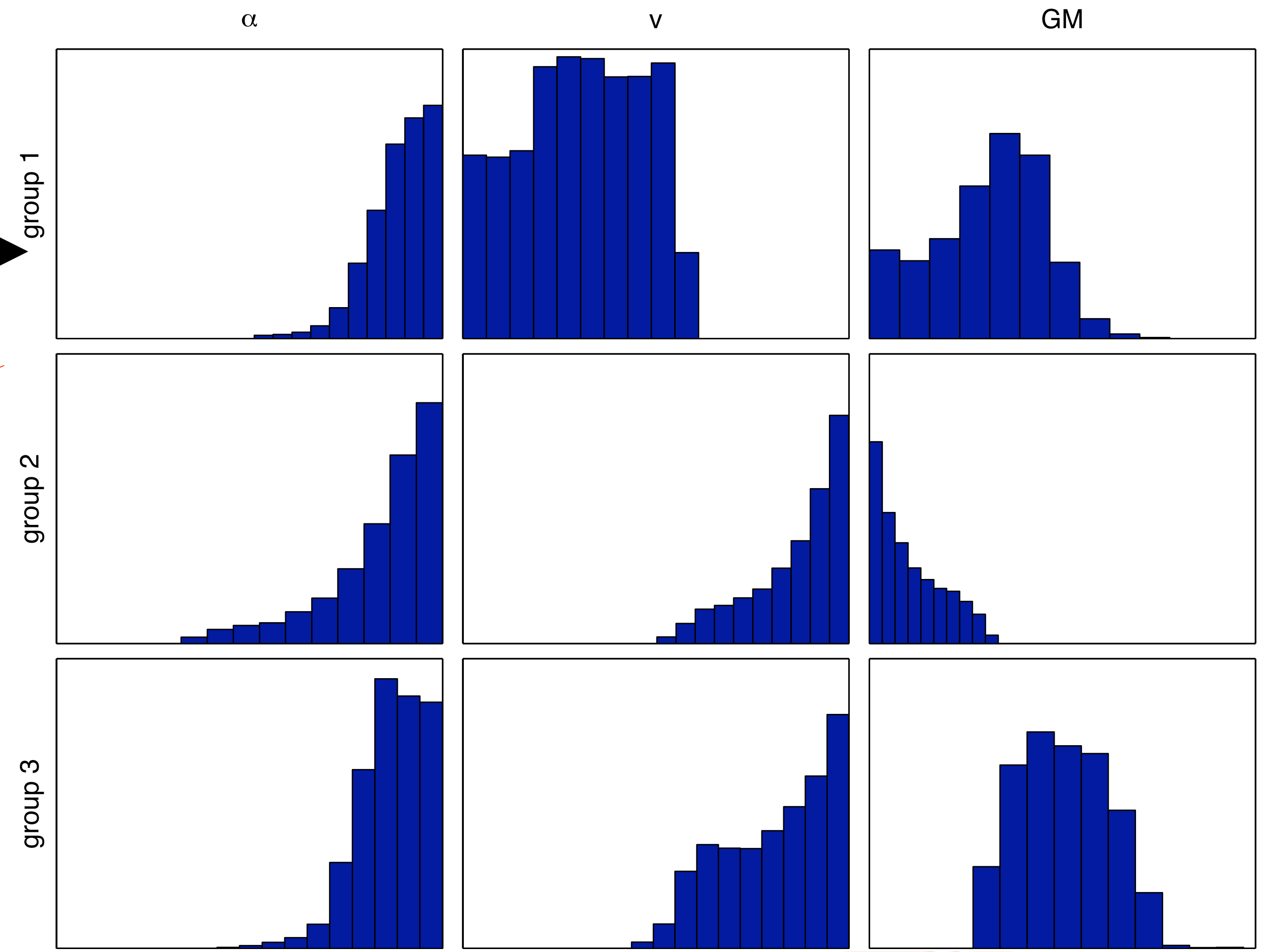
3 ways to produce more plausible solution

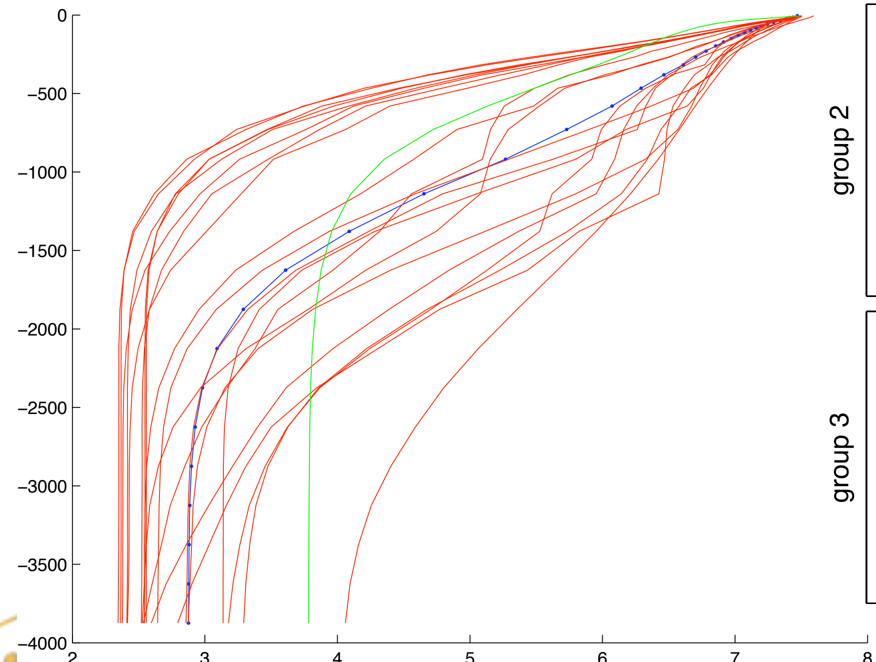




3 ways to produce more plausible solution

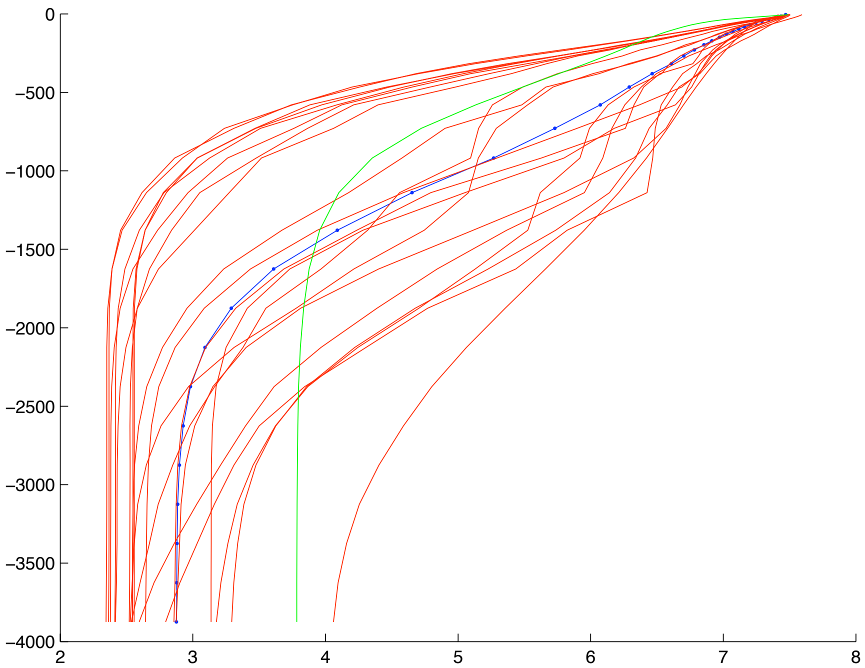
this row indicates high α, mid-to-low viscosity, mid-to-low GM





good choice of metric is essential:

for example, instead of minimizing distance from target, level-by-level:



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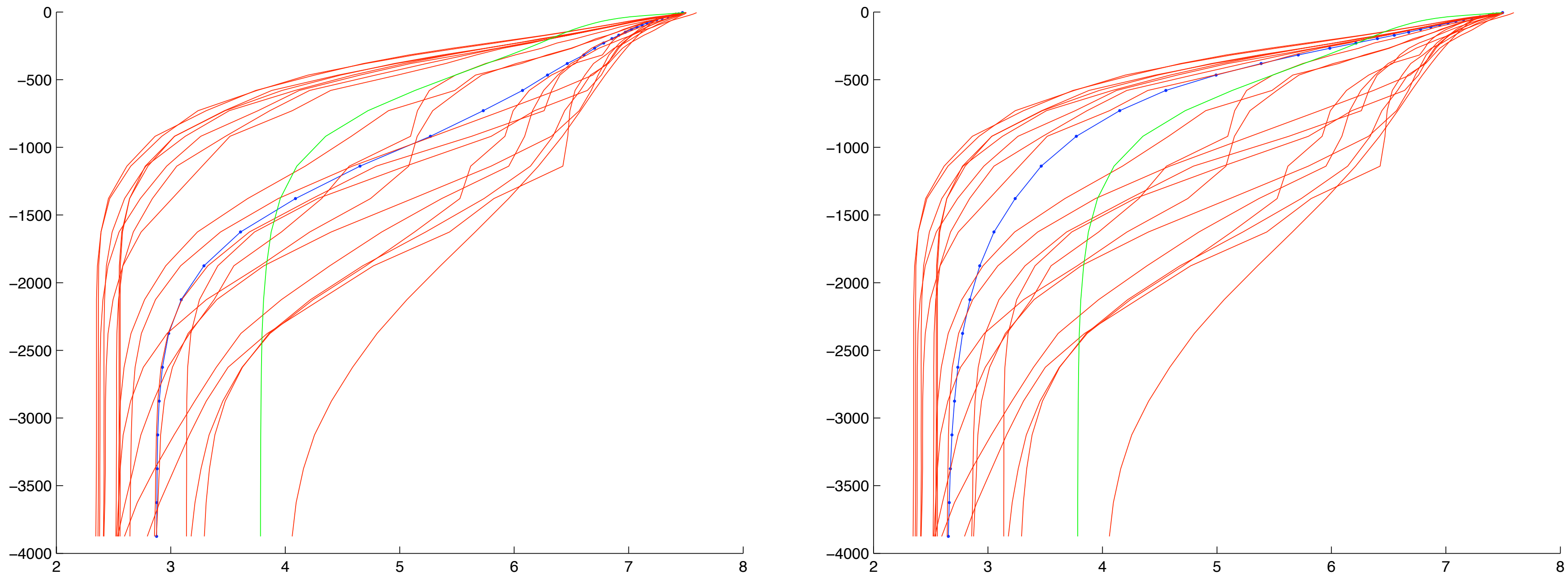

can allow for depth-independent bias
(so, select based on shape)

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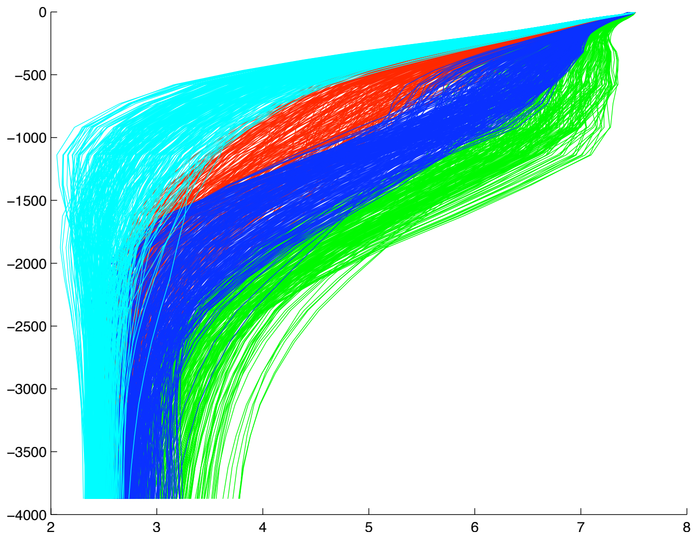
hard to fill 3-D param space with ocean model runs -- but it's easy now with the emulator



many profiles, produced by the emulator, grouped based on a clustering algorithm

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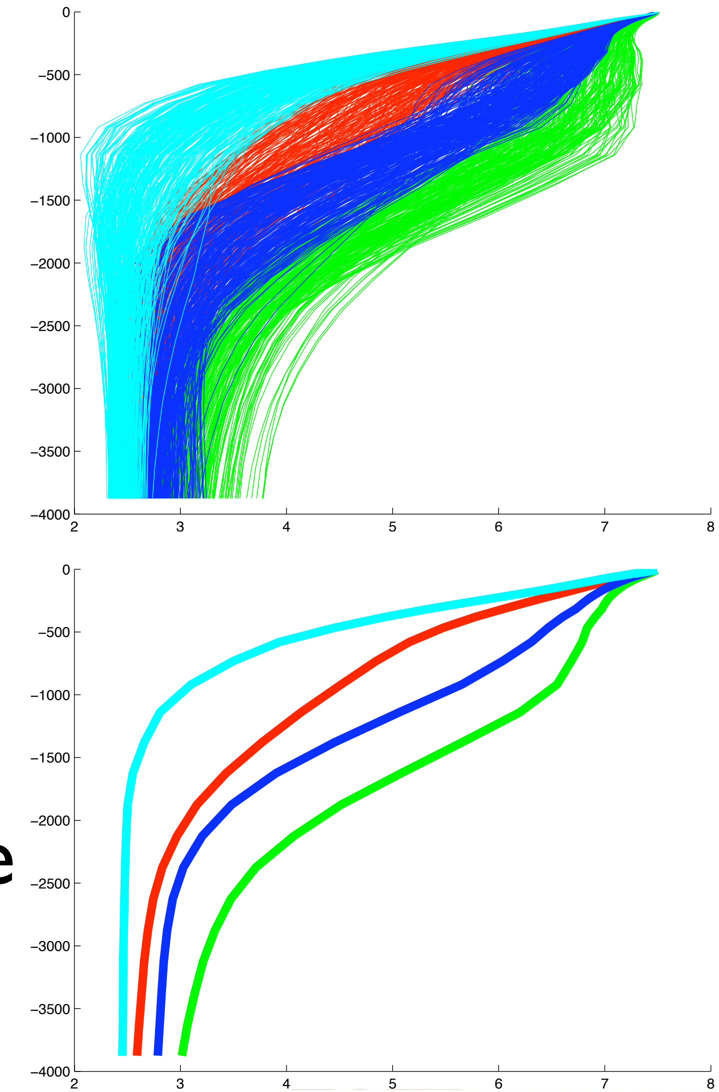

many profiles, produced by the emulator, grouped based on a clustering algorithm

then each associated with one representative profile

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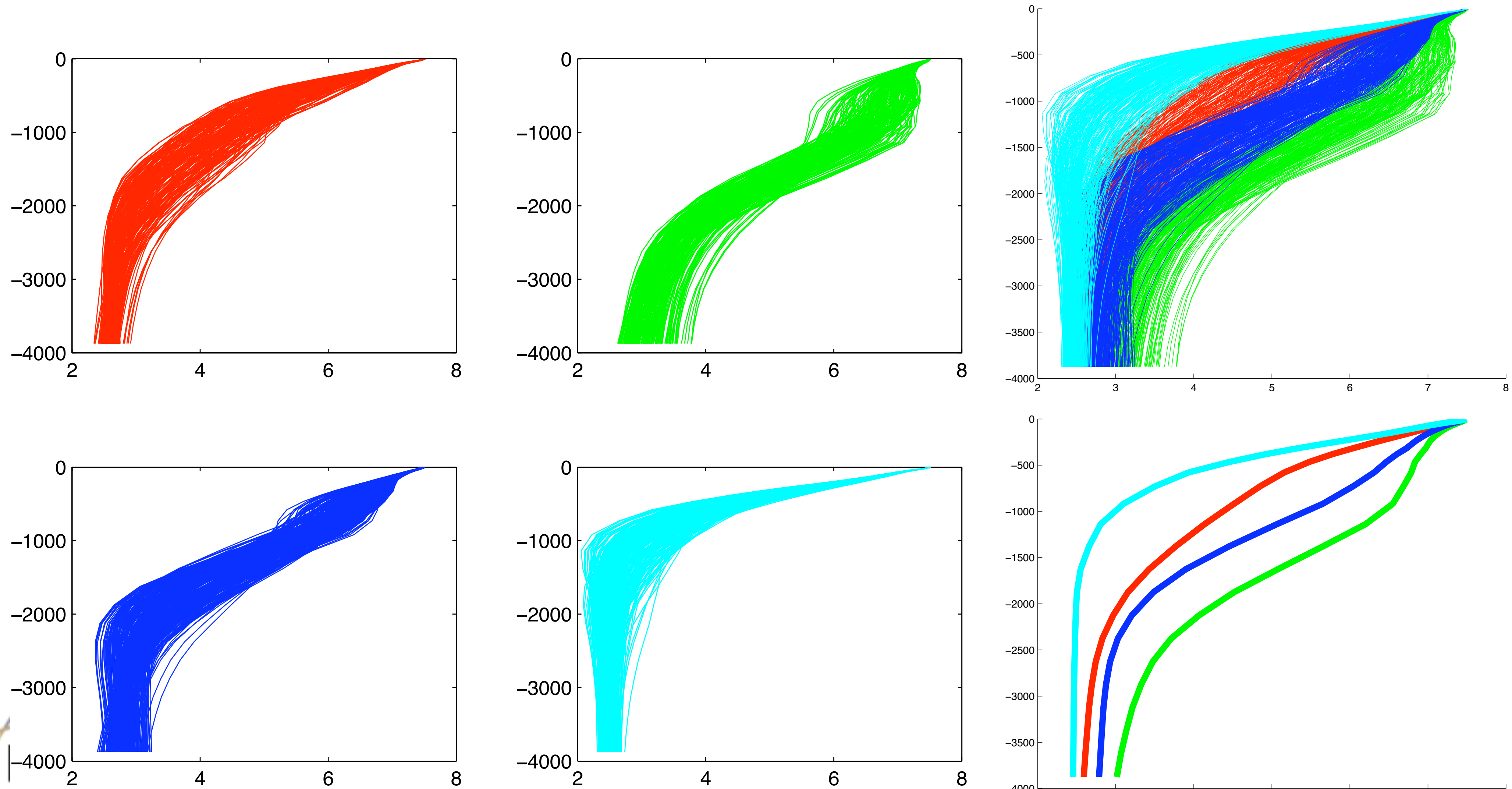

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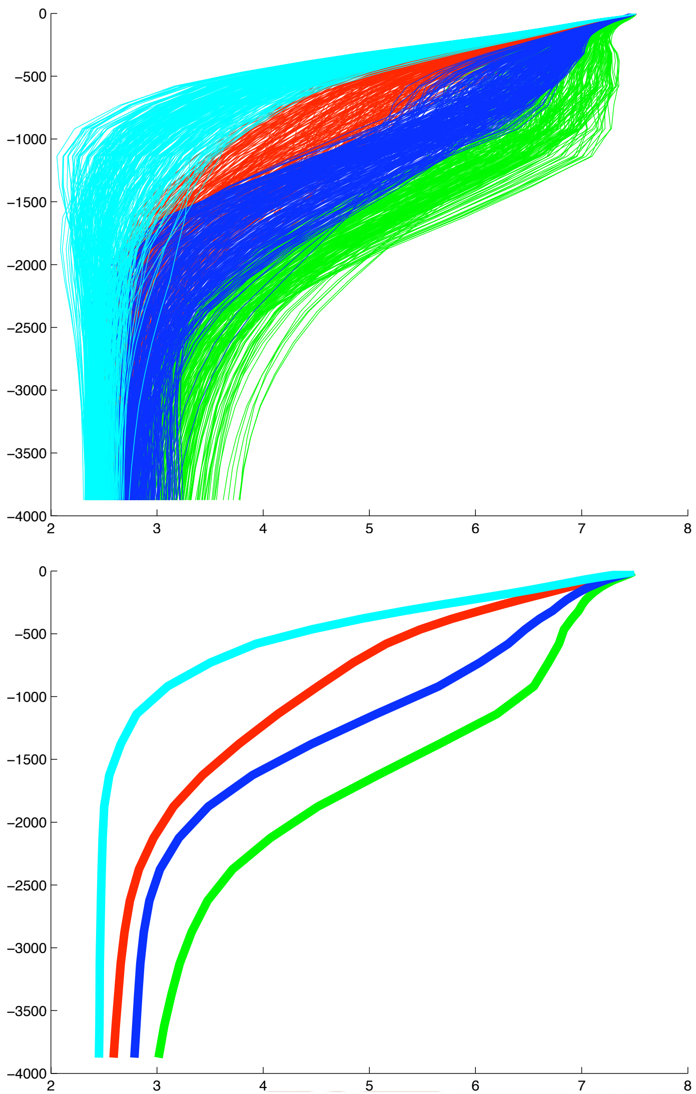

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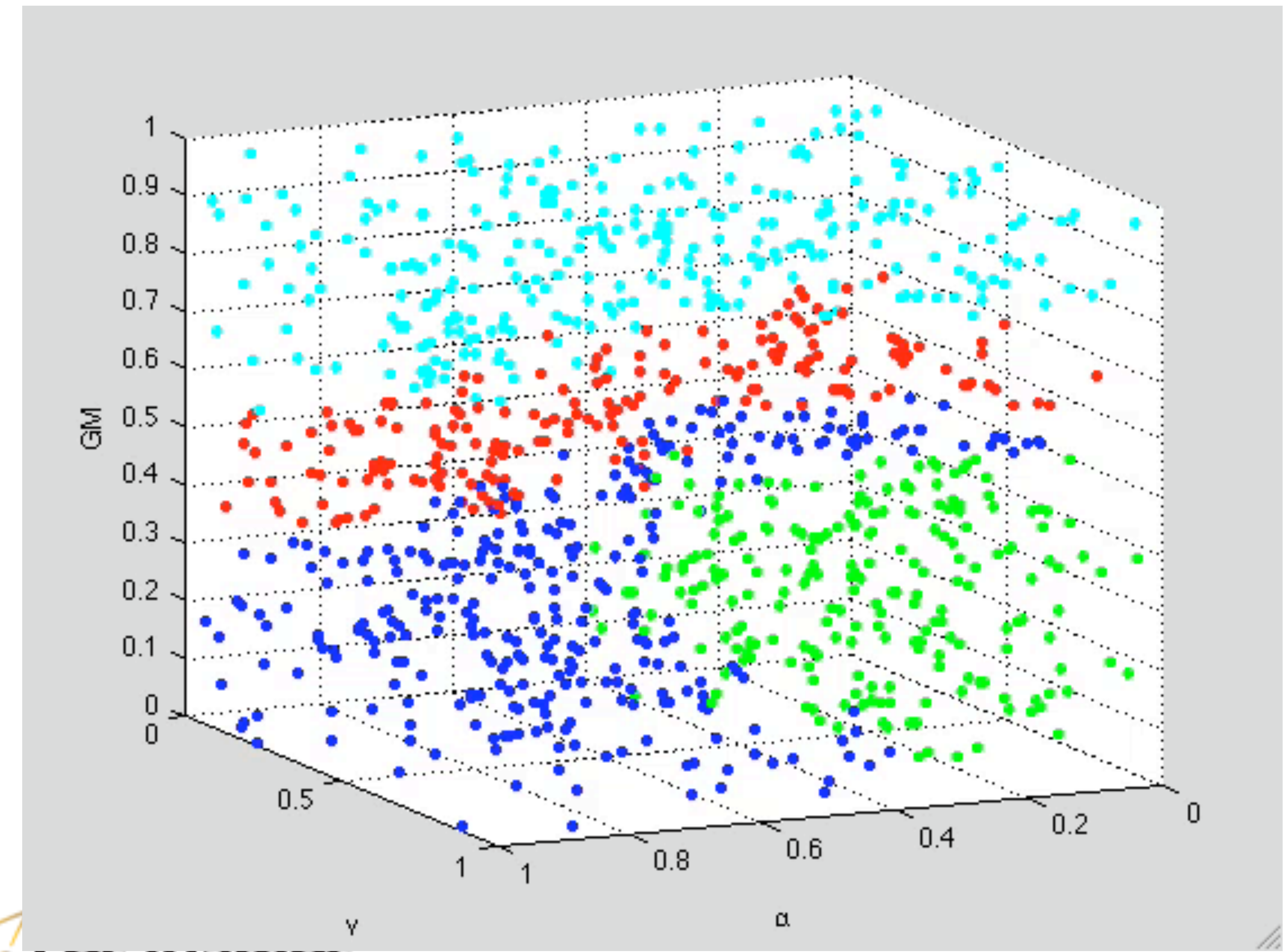

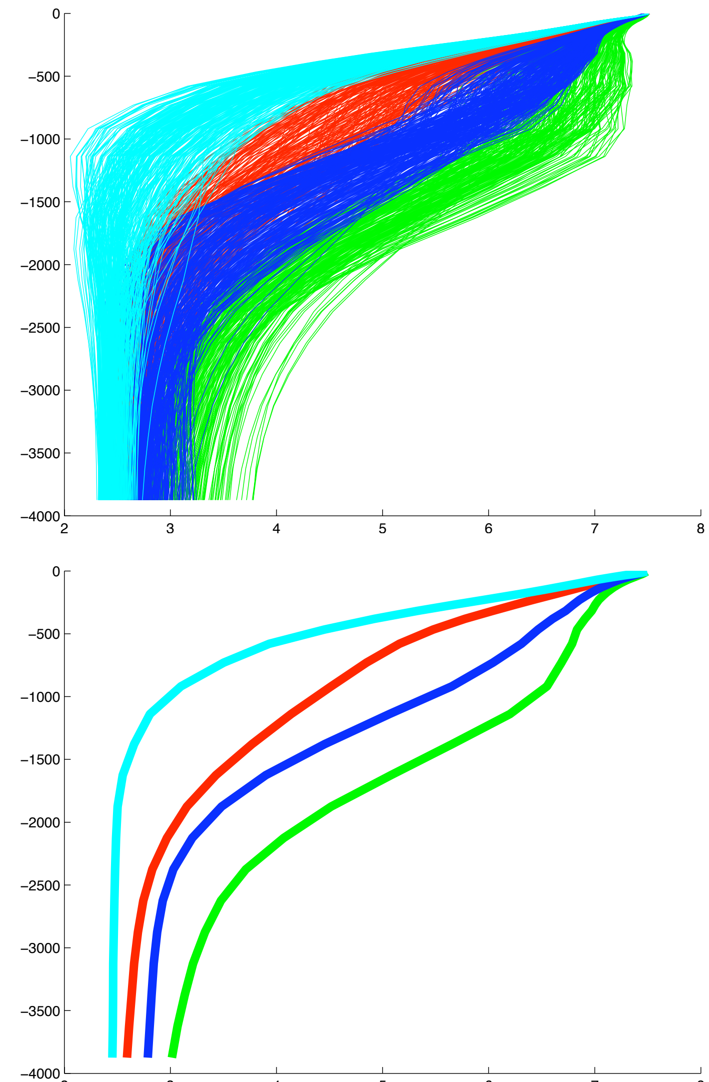

What comes next:

- refine our parameter estimation, still at low resolution
  - develop effective, discriminating measures
- move on to parameter estimation at higher resolution
- Take parameter set and apply to realistic ocean basin
  - compare 0.2 degree simulation, with α, to 0.1 degree simulation without

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and see if this is a better way to configure ocean models (and climate system models)

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